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Annual Index Issue

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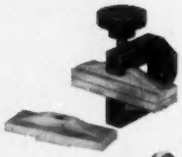

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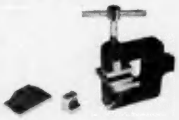

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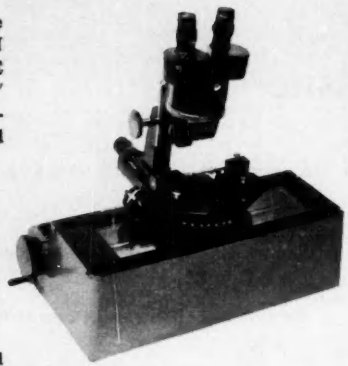

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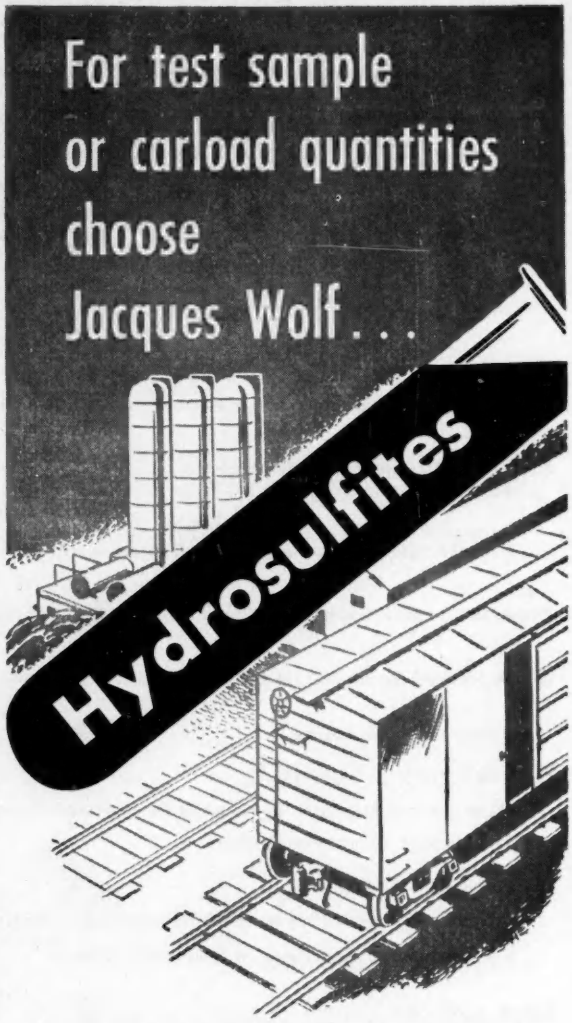

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TEXTILE RESEARCH JOURNAL

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Mechanism of Imparting Wrinkle Recovery to Cellulosic Fabrics

T. F. Cooke, J. H. Dusenbury,* R. H. Kienle,† and E. E. Lineken

American Cyanamid Company, Bound Brook, New Jersey

Introduction

A variety of terms has been used to describe "wrinkle recovery," including wrinkle resistance, crease resistance, and resiliency. Not only have a number of terms been employed, but also many methods have been used for measuring wrinkle recovery. We are reminded of another definition by Armour [2], as follows:

> The crease and the wrinkle, there isn't much doubt,
> Are alike in a number of ways,
> But the crease is the one that so quickly comes out
> While the wrinkle's the one that stays.

Wrinkle recovery in wearing apparel is, of course, very important from the standpoint of the appearance of the individual wearing the fabric. It is especially important with cellulosic fabrics which inherently are prone to wrinkle, especially under conditions of high humidity. The rapid growth in the use of textile resins on cellulosic fabrics has been due largely to the improvement in the wrinkle recovery brought about by these resin finishes. The importance of imparting wrinkle recovery to cellulosic fabrics is attested by the fact that some hundreds of millions of yards of cellulosic fabrics have been treated with melamine formaldehyde and urea formaldehyde during the past few years. The volume of resins used for this purpose has continued to increase.

In this paper, the term wrinkle recovery is used to describe the ability of a fabric to resist wrinkling, as well as to recover therefrom. The recovery may be rapid, in which case there will be an apparent resistance to the formation of a crease, or it may be slow.

Methods of Measurement

The most important methods of measuring wrinkle recovery include the following:

"Clenched Fist" [15]

One of the earliest methods was the "clenched-fist" method, which consists of crumpling a specimen of cloth by squeezing a wad of it tightly in the clenched fist. The resistance of the fabric to crushing, its behavior when the fist is rapidly opened, and the appearance of the crumpled fabric are observed. A fabric with good wrinkle recovery will resist crushing, spring back rapidly after the fist is opened, and show comparatively few wrinkles.

T.B.L. Method [1, 3]

The Tootal-Broadhurst-Lee Company many years ago introduced a simple technique for measuring the recovery of a fabric from wrinkling. In this method a piece of fabric 4 cm. long and 1 cm. wide is folded across its narrow dimension and placed beneath a 500-g. weight for 5 min. It is then allowed to recover for 3 min. while hung over a horizontal wire at the crease. The distance between the ends of the

* Present address: Textile Research Institute, Princeton, N. J.

† Present address: Stamford Research Laboratories, American Cyanamid Co., Stamford, Conn.

fabric sample in centimeters (the chord of the crease-recovery angle) is used as a measure of the wrinkle recovery of the fabric.

Roller Pressure Method [8]

The Stamford Laboratories of the American Cyanamid Company developed the Roller Pressure Method, which is an improvement over the T.B.L. method. In this test, the sample of fabric is creased by passage through two rolls which are pressed together by a constant weight. After passage between the rolls, the sample is dropped upon a knife edge. The silhouette of the creased specimen is projected on a rotatable, translucent screen, and the angle is measured at the apex with the aid of crossed hairs on a dial. This method has several advantages over the T.B.L. method including: (*a*) a uniform pressure, almost independent of the compressibility of the fabric, is applied to the specimen; (*b*) all handling of the specimen is eliminated after it is placed between the rollers of the tester; (*c*) the effect on the curvature of the sample caused by the weight of the fabric, which contributes to a large error in the T.B.L. method, is minimized by measuring the creasing angle at the vertex; and (*d*) the measurement of the angle, rather than the chord as in the T.B.L. method, results in improved accuracy, especially with fabrics that show high recovery angles.

Monsanto Wrinkle Recovery Tester [16]

A modification that minimized some of the variables of the T.B.L. method was developed by the Shirley Institute and further refined by the Monsanto Chemical Company. In this test, one end of the creased sample specimen is held in a jaw while the other hangs free and is brought into coincidence with the vertical line of the meter. The jaw in which the fabric sample is held is rotated to keep the free end of the fabric specimen in a vertical position, thus minimizing the errors caused by fabric weight in the T.B.L. tester. Its cheapness of manufacture and the fact that it gives a precision satisfactory for most purposes has led to its wide use in the industry.

Wear Test

The most reliable method of measuring wrinkle recovery is, of course, by wear tests. Tests made under actual service conditions are by their nature more reliable than laboratory accelerated test methods. In an accelerated laboratory test method, one is never sure in advance that the results obtained will correlate well with those made under actual service conditions. Of course, the disadvantages of carrying out apparel wear tests include (*a*) the cost of preparing garments, (*b*) the time and effort involved in making these tests and (*c*) the difficulty of measuring accurately the effects observed during the test.

Physical Aspects

A review of the literature shows that the physical aspects of the mechanism of wrinkle recovery have been studied by a number of people. Two of the most pertinent papers on this subject have been those of Gagliardi and Gruntfest [10] and Hamburger, Platt, and Morgan [12].

Gagliardi and Gruntfest applied various amounts of formaldehyde to viscose rayon yarn and determined the elongation at break of the yarns and the elastic recovery at 2% elongation. They found that the elastic recovery increased as the amount of formaldehyde increased. At the same time, the elongation at break was reduced. To show the relation between elasticity recovery on yarn and wrinkle resistance on fabrics, Gagliardi and Gruntfest applied the same amount of formaldehyde to a rayon challis and to an 80 × 80 cotton fabric and determined the fabric crease resistance by the recovery angle. They found that, as the concentration of formaldehyde was increased, the wrinkle resistance of both the rayon and cotton fabric increased.

Hamburger, Platt, and Morgan have analyzed textiles from an engineering standpoint. These authors stressed the fact that the average strain on most textile fabrics is of relatively low order and considerably less than that required for rupture. These authors also conclude ". . . that high immediate elastic deflection at low average tensile strains is an important fiber property in determining the crease recovery of fabrics."

Since Gagliardi and Gruntfest, and Hamburger, Platt, and Morgan have proposed that there is a correlation between fiber and yarn elasticity and the wrinkle recovery of the fabric composed of these fibers and yarns, one might expect that there would also be a correlation between fabric elasticity and wrinkle recovery. However, nothing could be found in the literature on measurements of the elasticity of resin-treated fabrics at relatively low exten-

sions to determine whether such data correlate well with the wrinkle recovery of the fabric. It was felt that such a study would be of great importance in a better understanding of the mechanism of imparting wrinkle recovery. In fact, it was thought most desirable to obtain the physical properties including the stress-strain properties of (1) fabrics, (2) the yarns making up the fabrics, and (3) the fibers of which the yarn was constructed. It was also considered important that crease-angle recovery measurements of the fabrics be made as well as appearance wear tests to determine whether a correlation exists between these sets of measurements. In addition, it was felt that other physical properties such as stiffness, tensile strength, and tear strength should be measured for comparative purposes.

Cotton

Measurements were made of untreated and various resin-treated 80 × 80 cotton fabrics (of plain weave) and of yarns taken from the fabrics. No single-fiber measurements were made on the cotton because of the large number of samples needed to obtain a satisfactory degree of precision. However, stress-strain measurements were obtained on untreated and resin-treated rayon filament fabric, the yarns going into this fabric, and the fibers of which the yarns were composed.

Cotton fabrics treated with several resin finishes with a wide range of properties were studied. These finishes included (*a*) 8% solids of a methylated melamine formaldehyde monomer, (*b*) 8% solids of an acid colloid made from the same melamine formaldehyde monomer, (*c*) 5% solids of an aqueous dispersion of a copolymer of styrene and ethyl acrylate, (*d*) 8% solids of the melamine formaldehyde monomer plus 2.4% solids of the styrene-ethyl acrylate copolymer, and (*e*) 5% solids of an aqueous dispersion of a polyvinyl acetate. Along with these resin treatments, the 80 × 80 cotton fabric processed with distilled water was included as a control.

The monomeric melamine formaldehyde treatment was chosen as a typical melamine formaldehyde wrinkle-resistant finish for cotton fabric. It has been shown by dye-staining techniques that applications of this monomeric melamine formaldehyde with an acid-forming catalyst cause the melamine formaldehyde to be deposited inside the cotton fiber.

The acid colloid treatment was primarily chosen in this study because the stiff finish produced gives some degree of "muss" resistance. This fabric does not readily fold into wrinkles but has little or no ability to recover from wrinkling. The acid colloid was prepared by adding lactic acid to an aqueous solution of the monomeric melamine formaldehyde. The melamine formaldehyde then polymerized on aging several hours to a state of partial polymerization. Dixon, Christopher, and Salley [9] showed by viscosity and diffusion measurements that, in this form, the acid colloid particle has an average size of 60–100 Å. Hunt, Blaine, and Rowen [14] have shown by low-temperature gas sorption measurements that the average diameter of the pores of a water-swollen cotton fiber is 16 Å and that of alkali-swollen cotton is 20 Å. From these measurements it would be expected that the acid colloid polymer particles would be too large to go inside the cotton fiber. The acid colloid was found by dye-staining techniques to be deposited on the outer surface of the cotton fiber.

The styrene-ethyl acrylate finish was chosen because it is a thermoplastic resin with elastomeric properties and imparts a small degree of wrinkle recovery to a cellulosic fabric. It has an average molecular weight of 20–40,000. It thus is too large to enter the interior of the cotton fiber, and consequently it is deposited on the surface of the fiber.

The combination finish of melamine formaldehyde and styrene-ethyl acrylate copolymer was included because this composition gives somewhat greater wrinkle recovery than melamine formaldehyde alone.

The polyvinyl acetate dispersion was chosen because it imparts a stiff finish but no wrinkle resistance. It also has an average molecular weight of 20–40,000 and is deposited on the surface of the fiber.

For control purposes, the 80 × 80 cotton fabric was water processed and evaluated in all the tests along with the resin-treated fabrics. Laboratory coats of a wrap-around style were made from each of the 5 treated fabrics along with the control fabric. One set of each of the laboratory coats was worn and evaluated by the personnel of one laboratory; the other set was worn and rated by the personnel of a different laboratory. The final rating given each finish was the average of the two wear tests. Evaluation of the laboratory coats was based on the appearance of the coats from a wrinkling standpoint after they had been worn. Evaluations were made each day after the coats were worn all day in the laboratory and again the following morning after

they had been hung on coat hangers the previous night, the average of the two observations being the final rating. The coats were worn for 8 days and then washed in a Bendix automatic washer with soap and soda ash through the normal cycle. After being washed and ironed, the coats were again worn for 8 days and then washed a second time. After the second wash, the coats treated with lactic acid colloid and polyvinyl acetate were removed from the test because of their poor appearance from the standpoint of wrinkle recovery. The remaining coats were worn for an additional 8 wearing days. The coats were rated on an arbitrary scale of 5, 4, 3, 2, 1, ranging in that order from good to poor. Since there were two coats made from each treated fabric, the final rating was obtained by adding together the ratings of each coat. Therefore, the best possible treatment had a rating number of 10 and the worst possible 2. Table I gives the ratings along with the 95% confidence limits of the means calculated for each set of data.

As can be seen, the combination of melamine formaldehyde and styrene-ethyl acrylate copolymer gave the best initial wrinkle recovery in the wear tests. The second best was the fabric treated with melamine formaldehyde. The styrene-ethyl acrylate copolymer gave a small but real improvement in wrinkle recovery over that of the untreated fabric. The lactic acid colloid of the melamine formaldehyde and the polyvinyl acetate both gave a fabric with poorer wrinkle recovery than the untreated control fabric. On a purely numerical basis, the difference between the lactic acid colloid of melamine formaldehyde and polyvinyl acetate could not be distinguished. The polyvinyl acetate treatment showed large wrinkles, whereas the lactic acid colloid of melamine formaldehyde showed a relatively larger number of considerably smaller wrinkles. The difference made it difficult for the observers to rank these two finishes properly.

It can be seen that the beneficial effect of the styrene-ethyl acrylate copolymer is reduced after the first washing. However, there is little change in the relative ratings of the coats in going from the first to second washing. After they had hung overnight, the coats treated with styrene-ethyl acrylate copolymer showed a marked improvement in appearance.

Fabric elasticities in the warp direction were measured on the fabrics at 5% extension, which was approximately 50% of the extension at break. The elasticity tests were made as follows: 1-in. strip specimens were cut, conditioned, and tested at 70°F and 65% R.H. Elasticity, extension at break, and breaking-strength measurements were made on the fabrics with an Instron Tensile Tester [13], using a gage length of 4 in. and a rate of extension of 50% per min. The sample was extended to 5% and immediately relaxed at the same rate, using the automatic extension cycle device. After a 5-min. rest, the sample was restretched through a second cycle. The amount of unrecovered deformation after this

TABLE I. WEAR TESTS *

Treatment	Rating numbers	95% confidence limits
Before Washing		
MF + S-EA copolymer	10.0	±0.1
MF	8.7	±0.2
S-EA copolymer	5.1	±0.3
Control	3.5	±0.3
LAC of MF	2.3	±0.2
PVA	2.4	±0.2
After First Washing		
MF + S-EA copolymer	8.5	±0.2
MF	8.9	±0.3
S-EA copolymer	3.5	±0.2
Control	2.7	±0.3
LAC of MF	2.1	±0.1
PVA	2.4	±0.3
After Second Washing		
MF + S-EA copolymer	7.0	±0.2
MF	7.0	±0.2
S-EA copolymer	2.8	±0.3
Control	2.0	±0.0

* Abbreviations used: MF, melamine formaldehyde; S-EA copolymer, styrene-ethyl acrylate copolymer; LAC of MF, lactic acid colloid of melamine formaldehyde; PVA, polyvinyl acetate. The control was water-processed untreated fabric.

TABLE II. FABRIC WARP EXTENSION AND ELASTICITY *

Wear rating	Treatment	% Extension at break	95% Confidence limits	% Elasticity	95% Confidence limits
10.0	MF + S-EA copolymer	9.0	±0.6	94.8	±1.0
8.7	MF	8.2	±0.3	88.2	±1.1
5.1	S-EA copolymer	11.6	±0.6	84.6	±1.3
3.5	Control	11.7	±0.6	72.8	±0.8
2.3	LAC of MF	10.4	±0.7	68.2	±0.8
2.4	PVA	11.5	±0.5	58.2	±0.7

* For key to abbreviations, see Table I.

time is called the permanent set of the sample. The remaining part is recoverable deformation (both immediate and delayed) and therefore is a measure of the samples' elasticity under the test conditions. The elasticity values were obtained from the following formula:

$$\text{percent elasticity} = \frac{\text{extension recovered after 5 min.}}{\text{total extension}} \times 100$$

A stress-strain curve for the wrinkle-resistant cotton fabric treated with monomeric melamine formaldehyde is given in Figure 1.

In the fill direction, since the extension at break was considerably higher, the elasticity measurements were carried out at 10% extension as well as 5%, the former value being approximately one-half the extension at break.

Table II gives a comparison of the wear-test ratings of the treated fabrics, the percent elasticity, and percent extension at break in the warp direction. Table III gives a similar comparison in the fill direction.

As can be seen from the above data, the percent elasticity measurements correlate very well with the wear-test rating, the fabric with the highest elastic recovery having the highest rating in the wear tests. It should be pointed out that, for the two fabrics with the highest wrinkle recovery, there is a decrease in the percent extension at break of the treated fabric. The elasticity of the fabric is higher at the lower strains, which according to Hamburger, Platt, and Morgan [12] are the strains usually encountered during normal use of a fabric.

Yarns were taken from the untreated and treated 80 × 80 cotton fabrics. Elasticity measurements were made on the Instron Tensile Tester in both warp and fill directions at a gage length of 10 in. and at a rate of extension of 50%/min. at various

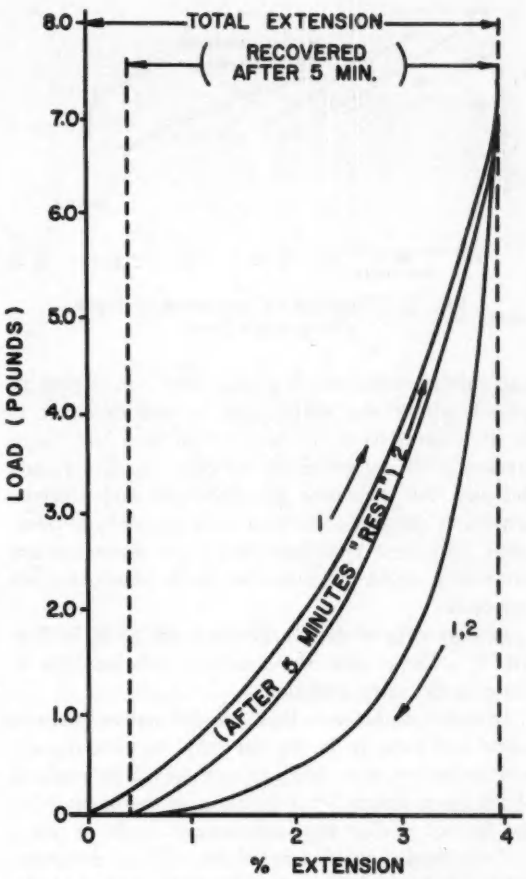

FIG. 1. *Stress-strain curve for cotton fabric treated with monomeric melamine formaldehyde.*

elongations from approximately 20% to 90% of the extension at break. The plot of the percent elasticity *versus* percent of extension at break in the warp direction is shown in Figure 2. As can be seen from these data, the correlation between yarn elasticities

TABLE III. FABRIC FILL EXTENSION AND ELASTICITY *

Wear rating	Treatment	% Extension at break	95% Confidence limits	% Elasticity at 5% extension	95% Confidence limits	% Elasticity at 10% extension	95% Confidence limits
10.0	MF + S-EA copolymer	15.3	±0.5	98.2	±0.3	94.2	±0.4
8.7	MF	16.0	±0.6	96.2	±0.4	89.1	±0.6
5.1	S-EA copolymer	21.0	±0.3	95.5	±0.3	84.4	±0.8
3.5	Control	22.2	±0.7	87.4	±0.7	75.6	±0.4
2.3	LAC of MF	19.5	±1.0	81.3	±0.4	57.4	±1.2
2.4	PVA	22.6	±0.9	71.8	±1.0	54.2	±0.6

* For key to abbreviations, see Table I.

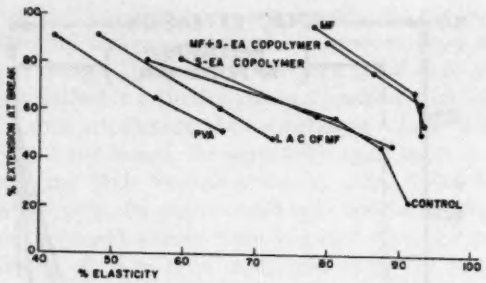

FIG. 2. *Elasticity* vs. *extension at break, cotton warp yarn.*

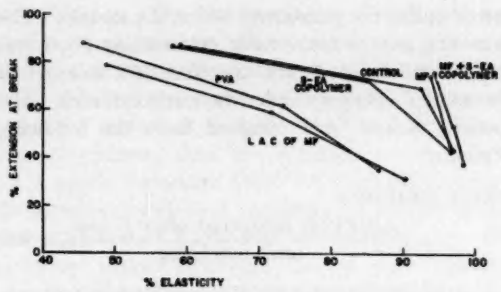

FIG. 3. *Elasticity* vs. *extension at break, cotton fill yarn.*

and fabric elasticities is good. The two noticeable places where the correlation is not excellent is in the comparison of the control and the yarns treated with styrene-ethyl acrylate copolymer, and between the melamine formaldehyde and styrene-ethyl acrylate plus the melamine formaldehyde treatment. In these two cases, the yarn elasticities are essentially equal, whereas the fabric elasticities are not equal.

Similar data in the fill direction are given in Figure 3. These data show similar relationships to those in the warp direction.

In order to be sure that the differences between fabric and yarn in the styrene-ethyl acrylate copolymer treatment were real and not caused by removal of the resin during the separation of the yarns from the fabric, similar treatments were made of yarn, and elasticities were determined. These measurements confirmed the earlier data, showing that the difference between fabric and yarn elasticity in the treatment with styrene-ethyl acrylate copolymer is a real one.

The correlation between the yarn and fabric elasticities is perhaps best seen in Figure 4, where a plot of the elasticity of the yarn *versus* the elasticity of the fabric is given for both the warp and fill directions. The correlation coefficient between the fabric and yarn elasticities is 0.94 in the warp direction, which means that the correlation is significant at better than the 95% confidence level. In the fill direction, the similar correlation coefficient is 0.79, indicating significant correlation at better than the 90% confidence level. These data indicate, therefore, that the increase in elasticity of the fabric caused by resin treatment is largely due to the increased elasticity of the yarns making up the fabric.

The immediate and delayed elastic recovery and

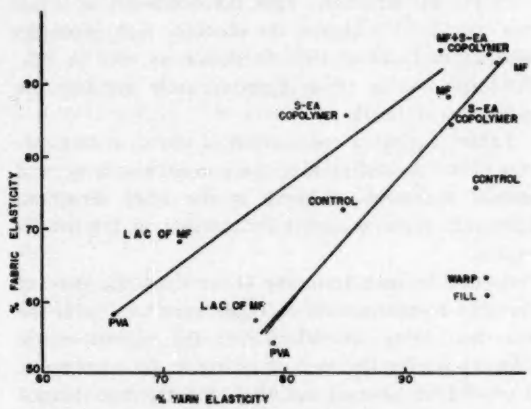

FIG. 4. *Elasticity of cotton fabric* vs. *cotton yarn.*

permanent set properties of the warp yarns taken from the fabrics treated with melamine formaldehyde, styrene-ethyl acrylate copolymer, and polyvinyl acetate as well as the untreated are plotted in Figure 5. These plots are similar in form to those of Susich and Backer [21]. The graphs show three areas: (1) the immediate elastic recovery, (2) delayed elastic recovery, and (3) permanent set. The plots show that the total elastic region of the yarns treated with melamine formaldehyde is the greatest of the four yarns shown. There is a similarity in the plots of the yarns treated with styrene-ethyl acrylate and polyvinyl acetate resin, with the elastic area of the former being greater than that of the latter. Similar plots for the fill yarns are given in Figure 6. These data show the same general relationships as the warp data.

Table IV gives the percent wrinkle recovery and the elasticity in both the warp and fill directions compared to the wear-test rating of the cotton fab-

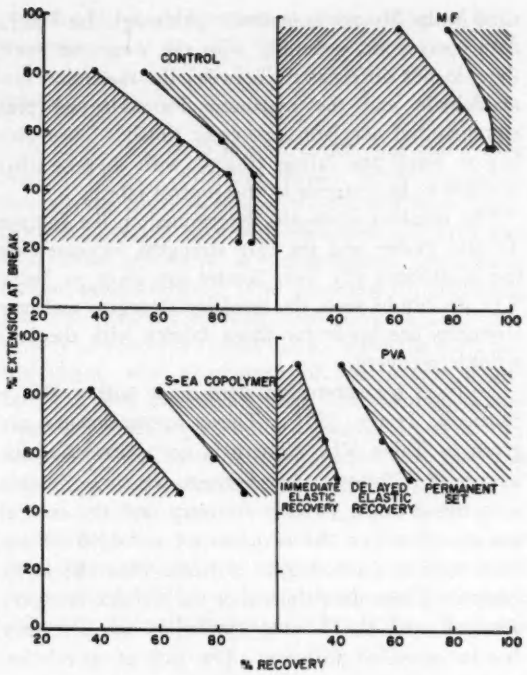

FIG. 5. *Elastic recovery and permanent set of treated cotton warp yarns and control.*

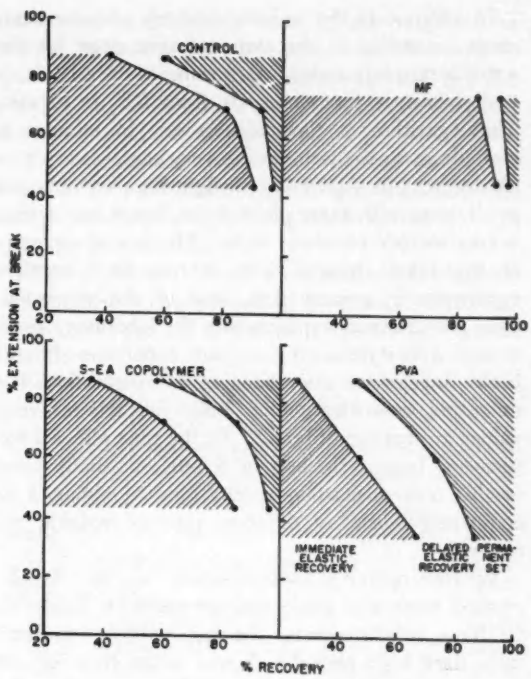

FIG. 6. *Elastic recovery and permanent set of treated cotton fill yarns and control.*

rics. As can be seen, the correlation among the wear rating number, percent wrinkle recovery, and percent elasticity is very good. The percent elasticity measurements made on the Instron Tensile Tester are more precise than the percent wrinkle recovery determined from the Monsanto wrinkle recovery tests, as shown by the 95% confidence limits of the two sets of measurements. These data show that the percent elasticity measurement using the Instron Tensile Tester could be used as a measure of the wrinkle recovery of a fabric.

The concept of obtaining greater wrinkle recovery with increased fabric elasticity has much wider implications than the treatment of cellulosic fabrics with resins. *It indicates that, to obtain optimum wrinkle recovery, the construction of a fabric of any fiber should be designed to obtain the greatest fabric elasticity.*

Plots of wear rating number with (1) wrinkle recovery and (2) elasticity are given in Figures 7 and 8, respectively. These graphs show that both wrinkle recovery and elasticity correlate well with the wear rating number.

TABLE IV. COMPARISON OF WRINKLE RECOVERY WITH ELASTICITY *

Wear rating	Treatment	% Wrinkle recovery	95% Confidence limits	% Elasticity	95% Confidence limits
		Warp			
10.0	MF + S-EA copolymer	78.8	±1.7	94.8	±1.0
8.7	MF	72.2	±2.1	88.2	±1.1
5.1	S-EA copolymer	50.0	±2.5	84.6	±1.3
3.5	Control	46.1	±1.7	72.8	±0.8
2.3	LAC of MF	36.7	±2.9	68.2	±0.8
2.4	PVA	32.8	±1.7	58.2	±0.7
		Fill			
10.0	MF + S-EA copolymer	78.9	±1.3	94.2	±0.4
8.7	MF	73.9	±1.0	89.1	±0.6
5.1	S-EA copolymer	49.4	±2.1	84.4	±0.8
3.5	Control	46.1	±2.5	75.6	±0.4
2.3	LAC of MF	33.4	±2.1	57.4	±1.2
2.4	PVA	32.2	±1.7	54.2	±0.6

* For key to abbreviations, see Table I.

In addition to the wrinkle-recovery measurements made according to the standard procedure for the wrinkle-recovery tester, measurements were made on each fabric at time intervals from 0.5 to 10 min. The logarithm of time of recovery in minutes is plotted *versus* the wrinkle-recovery angle (warp plus fill degrees) in Figure 9. Straight lines are obtained in all cases with these plots of the logarithm of time *versus* wrinkle-recovery angle. The rate of recovery of the fabric treated with styrene-ethyl acrylate copolymer is greater than that of the untreated. This phenomenon explains why the laboratory coats treated with styrene-ethyl acrylate copolymer showed better appearance after hanging overnight than the untreated, even though the 5-min. wrinkle-recovery values are not far different. In the time allowed for recovery from wrinkling of 5 min., normally used in this test, misleading results may be obtained in comparing fabrics of different rates of wrinkle recovery.

Wrinkle-recovery measurements by the T.B.L. method were also made and are given in Table V. In these measurements, the test sample was bent upon itself for a period of 5 min. rather than for the 3 min. normally used in the T.B.L. procedure, in order for the time to be comparable to the 5 min. used in the Monsanto method. Although the T.B.L. data correspond generally with the wear-test rank, they do not differentiate between the melamine formaldehyde and the melamine formaldehyde plus styrene-ethyl acrylate copolymer finish. They also fail to show the fabric treated with styrene-ethyl acrylate to be superior to the control fabric.

The breaking strengths determined on the Instron Tensile Tester and the tear strengths measured on the Elmendorf [6] Tear Tester are given in Table VI. As can be seen, the breaking strengths and tear strengths are lower for those fabrics with the best wrinkle recovery.

Stiffness measurements were made with a Pierce Stiffness Tester [20]. These measurements are given in Table VII. There is no appreciable difference in stiffness ratings between the three finishes with the greatest wrinkle recovery and the control fabric. However, the two poorest wrinkle resistant finishes have much higher stiffness than the other fabrics. These data show that the wrinkle recovery obtained with the finishes studied is not primarily due to increased stiffness. The lack of correlation between stiffness and wear-test results is important. *It shows that the ability of a fabric to recover from*

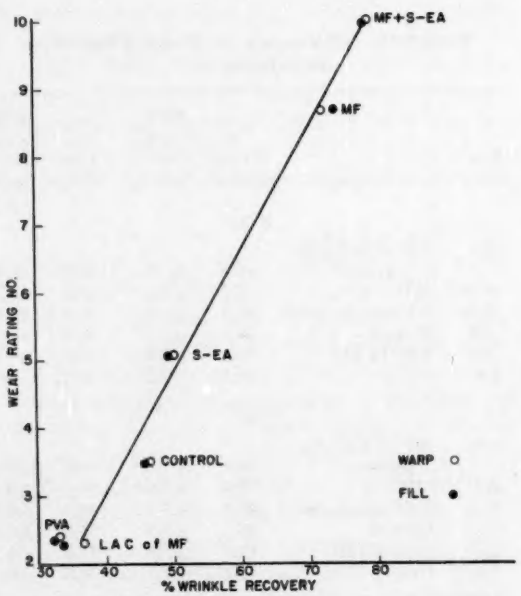

FIG. 7. *Wear rating* vs. *wrinkle recovery, cotton fabric.*

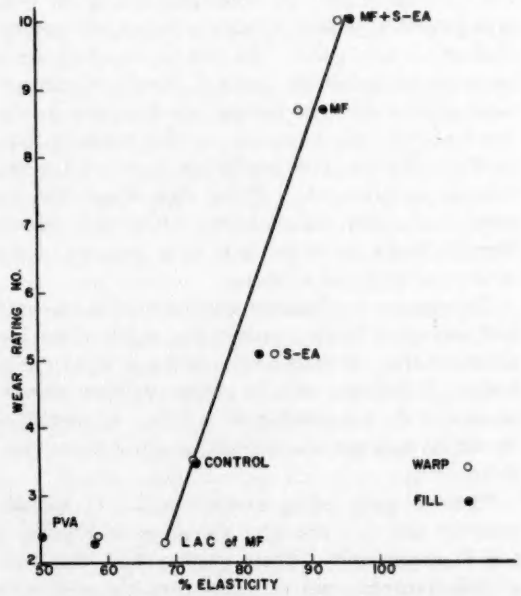

FIG. 8. *Wear rating* vs. *elasticity, cotton fabric.*

creasing is more important than its ability to resist creasing.

Rayon

A study similar to that of cotton was made with viscose rayon. Filament rayon fabric furnished through the courtesy of the American Viscose Company was treated with both melamine and urea formaldehyde, and physical measurements were made on the treated fabrics. The melamine formaldehyde was the monomeric methylated product used previously to treat the cotton fabric, while the urea formaldehyde was a mixture of monomeric monomethylol and dimethylol urea. In addition, yarns from which the rayon fabrics were made were likewise treated. Physical measurements were made on these yarns and on fibers taken from the treated yarns.

The filament rayon fabric was a 2 × 1 twill weave of 150/40 yarn. Typical treatments of melamine and urea formaldehyde were chosen. These treatments consisted of 7.5% solids of monomeric methylated melamine formaldehyde and 15% solids of monomeric urea formaldehyde based on the weight of the rayon. In addition, a water-processed fabric was included in the study. The yarns were laid out flat, parallel to one another, and then processed under the same conditions as the fabric.

The percent elasticities were measured on the fabric at various percentages of the extension at break, using the same method described earlier for the treated cotton fabrics.

Figures 10 and 11 are plots of percent elasticity of the fabric *versus* percent of the extension at break in the warp and fill directions, respectively. As can

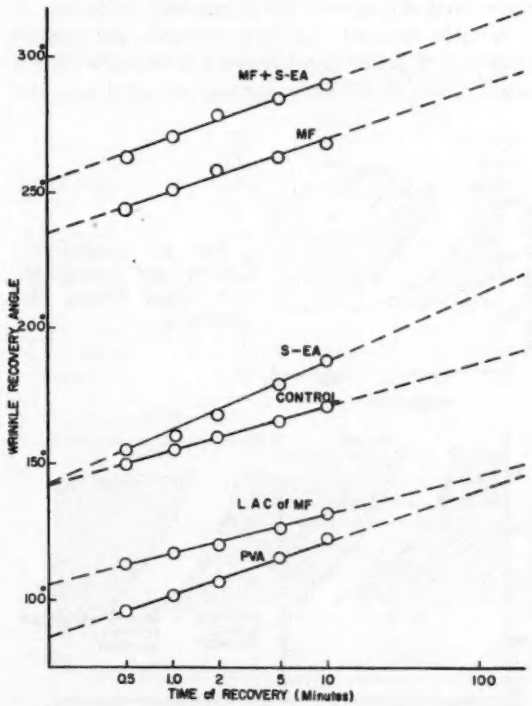

FIG. 9. *Wrinkle recovery* vs. *time, cotton fabric.*

TABLE V. T.B.L. WRINKLE-RECOVERY MEASUREMENTS *

Rating	Treatment	Wrinkle recovery Warp+Fill (cm.)	95% Confidence limits
10.0	MF + S-EA copolymer	7.2	±0.2
8.7	MF	7.2	±0.2
5.1	S-EA copolymer	4.5	±0.3
3.5	Control	4.3	±0.2
2.3	LAC of MF	3.4	±0.2
2.4	PVA	3.3	±0.2

TABLE VI. BREAKING AND TEAR STRENGTHS (FILL DIRECTION) *

Wear rating	Treatment	Breaking strength (lbs.)	95% Confidence limits	Tear strength (lbs.)	95% Confidence limits
10.0	MF + S-EA copolymer	21.0	±0.9	0.60	±0.19
8.7	MF	22.3	±1.6	0.64	±0.19
5.1	S-EA copolymer	35.0	±2.0	1.08	±0.20
3.5	Control	31.1	±1.7	0.88	±0.11
2.3	LAC of MF	36.9	±4.7	0.87	±0.20
2.4	PVA	36.5	±3.3	1.05	±0.21

TABLE VII. PIERCE STIFFNESS MEASUREMENTS *

Wear rating	Treatment	Stiffness (in.)	95% Confidence limits
10.0	MF + S-EA copolymer	1.8	±0.1
8.7	MF	1.7	±0.1
5.1	S-EA copolymer	1.8	±0.1
3.5	Control	1.6	±0.1
2.3	LAC of MF	4.1	±0.2
2.4	PVA	4.3	±0.1

* For key to abbreviations, see Table I.

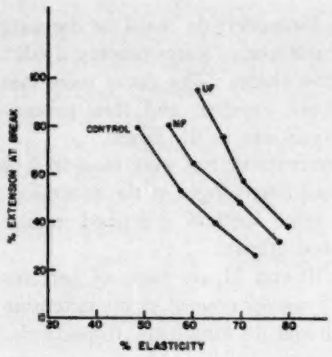

FIG. 10. *Elasticity* vs. *extension at break, rayon fabric, warp direction.*

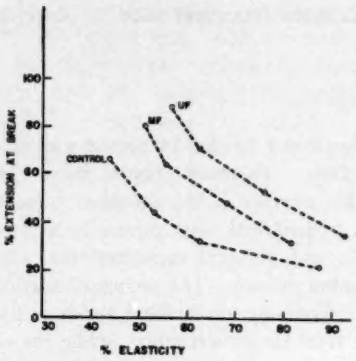

FIG. 11. *Elasticity,* vs. *extension at break, rayon fabric, fill direction.*

be seen from these plots, the melamine formaldehyde and urea formaldehyde treatments changed the elasticity of rayon in much the same way as did that of the cotton fabric. The percent elasticity of the rayon treated with urea formaldehyde is somewhat more than that of the melamine formaldehyde, but twice as much solids was used on the fabric in the former case. It should be noted that the elasticity is higher at the lower strain regions, as is the care with cotton.

The immediate and delayed elastic recovery and the permanent set of the fabrics that were water processed and melamine and urea formaldehyde treated are plotted for the warp direction in Figure 12 and for the fill direction in Figure 13 in the same manner used for the cotton yarn. These plots show that the total elastic area (immediate plus delayed) is increased in going from the control to the 7.5% melamine formaldehyde to the 15% urea formaldehyde treatments. There seems to be little change in the delayed elastic recovery area, whereas the immediate elastic recovery area increases with a corresponding decrease in the permanent set area.

Wrinkle recovery, breaking strength, and percent extension at break measurements were made on the rayon fabric in the same manner as previously de-

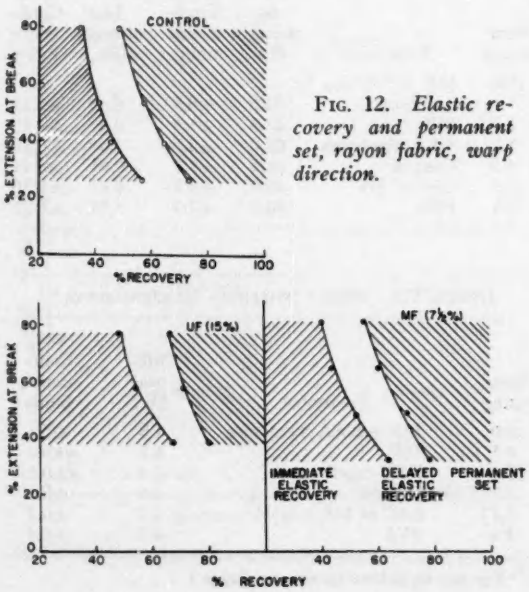

FIG. 12. *Elastic recovery and permanent set, rayon fabric, warp direction.*

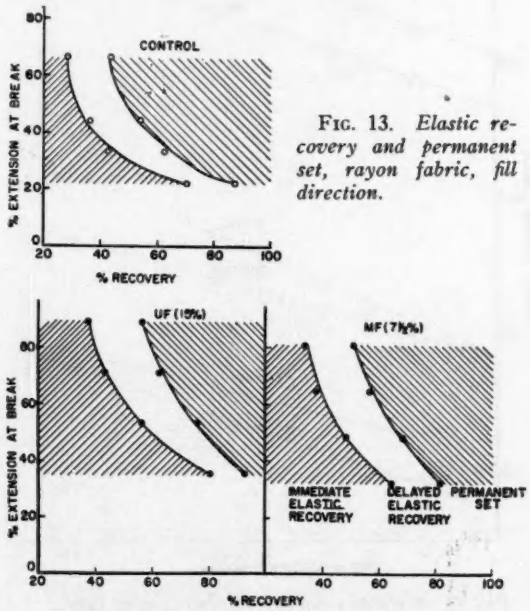

FIG. 13. *Elastic recovery and permanent set, rayon fabric, fill direction.*

scribed for the cotton fabric. These data are given in Table VIII along with the elasticity measurements. These elasticity measurements, as well as those given in Tables IX and X, were made at 50% of the ultimate elongation. These data show that the percent elasticity increased with decreasing extension at break as was the case with the cotton fabric. The breaking-strength data show little change with the increase in elasticity of the treated rayon fabric, however, contrary to the data obtained on the cotton fabric.

The good correlation between percent elasticity and wrinkle recovery is perhaps best shown by Figure 14, which gives a plot of one against the other.

Similar physical measurements were also made on filament rayon yarn treated with melamine and urea formaldehyde. These data are given in Table IX. The percent elasticity of the yarn treated with 15% solids of urea formaldehyde was greater than that of the yarn treated with 7.5% solids of melamine formaldehyde, which in turn was greater than that of the water-processed yarn. The percent extension at break decreased as the percent elasticity increased. These general relationships are similar to those found for the rayon fabric.

Figure 15 gives a plot of the elasticity of the fabric *versus* that of the yarn in both warp and fill directions. Although there are only three points on the curves, it can be seen that there is good correlation between the elasticity of the fabric and that of the yarn. It therefore appears that in rayon as well as in cotton the increase in the elasticity of the fabric is due largely to the increase in the elasticity of the yarn.

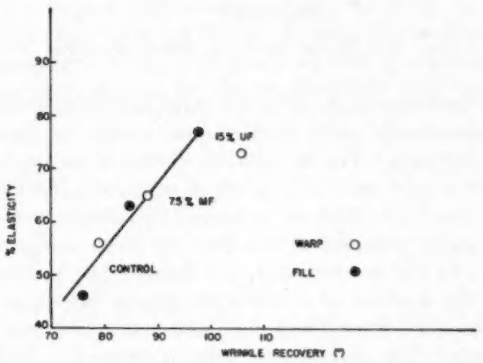

FIG. 14. *Wrinkle recovery vs. elasticity, rayon fabric.*

TABLE VIII. PHYSICAL PROPERTIES OF RAYON FABRIC

Treatment	% Elasticity	95% Confidence limits	Wrinkle recovery angle	95% Confidence limits	% Extension at break	95% Confidence limits	Breaking strength (lbs.)	95% Confidence limits
			Warp					
15% UF*	73	±0.7	106°	±3	13	±1.0	86	±4.2
7.5% MF†	65	±1.9	88°	±4	16	±0.9	83	±4.6
Control	56	±1.5	79°	±4	19	±1.5	76	±4.9
			Fill					
15% UF*	77	±1.0	98°	±2	14	±1.4	41	±3.8
7.5% MF†	63	±0.2	85°	±4	16	±1.0	42	±2.8
Control	46	±0.7	76°	±5	23	±2.5	47	±2.2

* Urea formaldehyde.
† Melamine formaldehyde.

TABLE IX. PHYSICAL PROPERTIES OF RAYON YARN

Treatment	% Elasticity	95% Confidence limits	% Extension at break	95% Confidence limits	Breaking strength (g.)	95% Confidence limits
15% UF*	89	±1.0	4.2	±0.7	306	±19
7.5% MF†	77	±1.2	7.5	±0.8	267	±21
Control	52	±0.4	16.8	±0.6	334	±08

* Urea formaldehyde.
† Melamine formaldehyde.

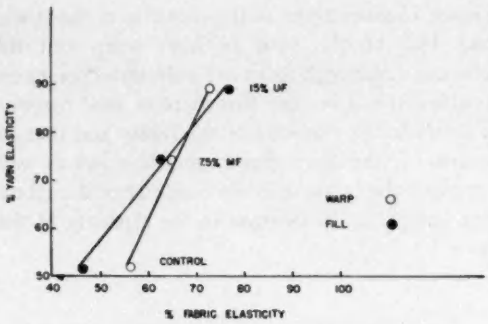

FIG. 15. *Rayon elasticity, fabric* vs. *yarn.*

Fibers were taken from the yarns and stress-strain measurements made in a manner similar to those for the yarn. The stress-strain curves of the rayon fiber treated with 15% solids of urea formaldehyde and the 7.5% solids of melamine formaldehyde and the water-processed control fiber are given in Figure 16. As can be seen, both the Hooke's law portion and the modulus of elasticity are greater in the case of the fibers treated with melamine and urea formaldehyde. The extension at break is reduced in both cases, the urea formaldehyde-treated fiber showing the greatest reduction.

The physical properties of the rayon fibers are given in Table X. The change in elasticity of the fiber with treatment is analogous to that of the yarn. It will be noted that the elasticity increased with decreasing extension at break with the rayon fibers in a similar manner to that of the yarn.

Figure 17 gives a plot of the elasticity of the fiber *versus* that of the yarn. As can be seen, the correlation between the fiber and yarn elasticities is good.

It is interesting to note that there is a good correlation among the elasticity and extension at break values, respectively, of the rayon fabric, yarn, and fiber. The same relative increase in the elasticity

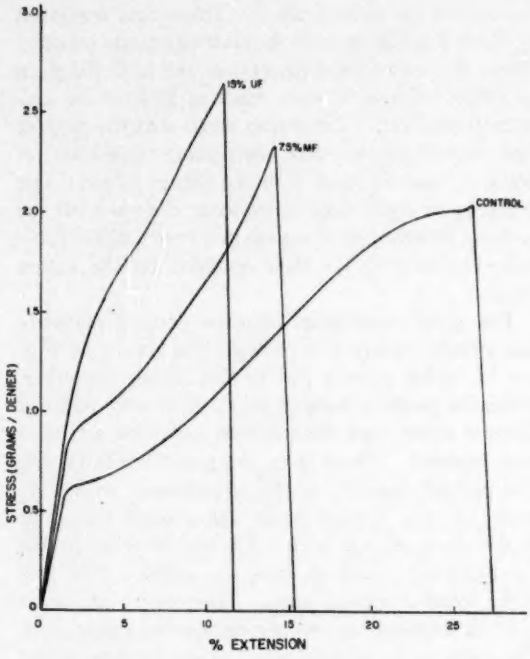

FIG. 16. *Stress-strain curves for rayon fibers.*

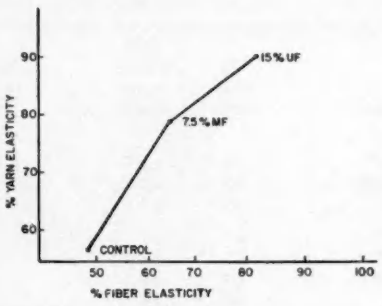

FIG. 17. *Rayon elasticity, fabric* vs. *yarn.*

TABLE X. RAYON FIBERS

Treatment	% Elasticity	95% Confidence limits	% Extension at break	95% Confidence limits	Breaking strength (g./den.)	95% Confidence limits
15% UF*	80.2	±1.3	10.8	±0.5	2.49	±0.2
7.5% MF†	64.5	±2.3	14.2	±2.0	2.07	±0.1
Control	48.8	±3.6	23.9	±1.1	2.09	±0.1

* Urea formaldehyde.
† Melamine formaldehyde.

of the fibers with melamine and urea formaldehyde treatment was present in the yarn and the fabric. Also, the same relative decrease in the percent extension at break of the fibers was present in the yarn and in the fabric. The correlation in breaking-strength data is not as good as for elasticity and extension at break. The breaking strength of the yarn shows some decrease with melamine and urea formaldehyde treatment, whereas the fiber and fabric breaking strengths are equal to or greater than those of the untreated. The excellent correlation between the elasticities of the rayon fabric, yarn, and fiber indicates that the increase in elasticity of the building blocks of the fabric, *i.e.*, the fibers, by the melamine and urea formaldehyde treatment is carried through the yarn to the fabric. The analogy between the changes in the physical properties of the fiber, yarn, and fabric with treatment is best illustrated by Figure 18, which gives the load-extension curves for the untreated and urea formaldehyde counterparts. The increase in the elasticity of the fabric in turn results in increased wrinkle resistance.

Before leaving the physical aspects of the mechanism of imparting wrinkle recovery to cellulose fabrics, further consideration should be given to the elastomeric type of resin. It was shown that an increase in wrinkle recovery was brought about by the application of an aqueous dispersion of a copoly-

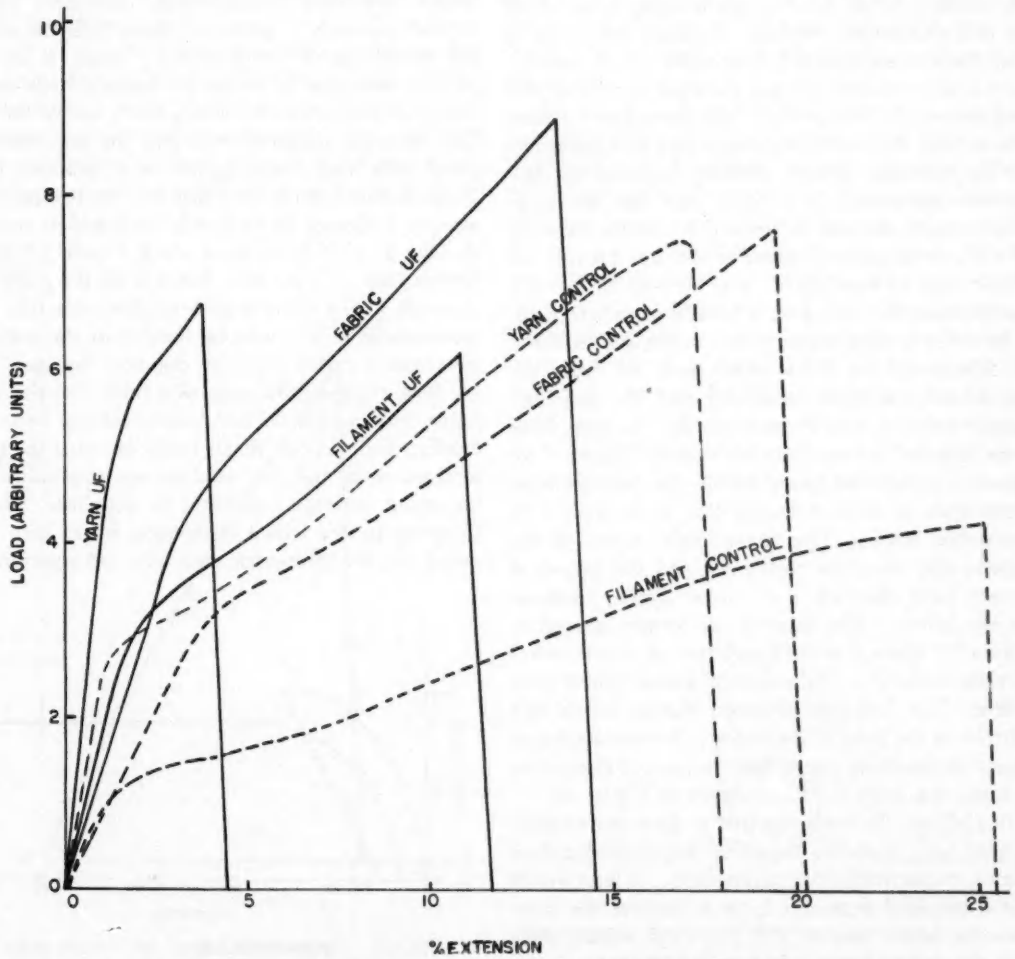

FIG. 18. *Load-extension curves, treated and untreated rayon.*

mer of styrene-ethyl acrylate to cotton fabric. This copolymer applied alone improved the wrinkle recovery of the cotton fabric. When it was applied in combination with a melamine formaldehyde monomer, an increase in wrinkle recovery was obtained over that of the application of the melamine formaldehyde alone. It was also shown that an application of an aqueous dispersion of polyvinyl acetate resin to cotton fabric did not provide an increase but rather a decrease in wrinkle recovery. Both of these resins have an average molecular weight of 20–40,000, and the size of the molecule is therefore so large that both resins are deposited on the surface of the fiber. One possibility for explaining the wrinkle recovery obtained by the styrene-ethyl acrylate copolymer is that an elastic type of yarn-to-yarn bonding is imparted by this elastomeric product. Another possibility is that there is a decrease in the coefficient of yarn-to-yarn friction resulting from a coating, probably discontinuous, of the yarn by the elastomer. Either one of both of these mechanisms may be responsible for the increased wrinkle recovery imparted by elastomeric polymers. It is postulated that the polyvinyl acetate did not increase the wrinkle recovery of the cotton fabric because it did not provide an elastic type of bonding of yarn to yarn and/or did not decrease the coefficient of friction of yarn to yarn.

In order to obtain data which might add evidence to this postulate, films were made of both the styrene-ethyl acrylate copolymer and the polyvinyl acetate polymer, and stress-strain data of these films were obtained on the Instron Tensile Tester. The films were prepared by air drying the same aqueous dispersions of these polymers that were applied to the cotton fabric. The stress-strain curves of the styrene-ethyl acrylate copolymer and the polyvinyl acetate were obtained in a manner similar to those for the fabrics. The data for the former, plotted in Figure 19, show that the copolymer of styrene-ethyl acrylate is elastic. The polyvinyl acetate film is very brittle. The first film prepared was so brittle that it broke in the jaws of the tester. A second attempt gave a stress-strain curve, but the percent elongation at break was only 1.5%, as shown in Figure 20.

In addition, the force required to draw out a single severed yarn from the untreated and treated cotton fabrics, respectively, was determined. It was found that it required a greater force to remove the yarn from the fabric treated with polyvinyl acetate than from the control fabric. It required less force, however, to remove the yarn from the cotton fabric treated with styrene-ethyl acrylate than from the control fabric. These measurements indicate that the coefficient of yarn-to-yarn friction of the fabric treated with styrene-ethyl acrylate was lower than that of the control.

These data, therefore, are in agreement with the concept that the increase in elasticity of fabric treated with an elastomeric type of polymer is brought about by an elastic bonding of yarn to yarn and/or by a decrease in the coefficient of friction of yarn to yarn.

Chemical Aspects

The literature of the mechanism by which melamine and urea formaldehyde monomers impart wrinkle recovery to cellulosic fibers from the chemical standpoint is controversial. Since it is well known that urea or melamine formaldehyde monomers can polymerize to form a resin, one of the earliest theories advanced was that the monomer reacted with itself when applied to a cellulosic fiber. Some workers still believe that this mechanism operates, as evidenced by an article published as recently as May of 1954 [18], from which I quote: "Others believe that . . . the resin formers fill the pores and channels of the fibers with insoluble resin that to a considerable extent may be bonded to the cellulose by physical rather than by chemical linkages." It has been proposed by some who think that the resin polymerizes within the cellulosic fibers that hydrogen bonding and van der Waals forces between the polymerized resin and the cellulose are responsible for imparting wrinkle recovery to cellulosic fabrics. Contrary to this school of thought, it has been proposed that the monomeric melamine and urea formal-

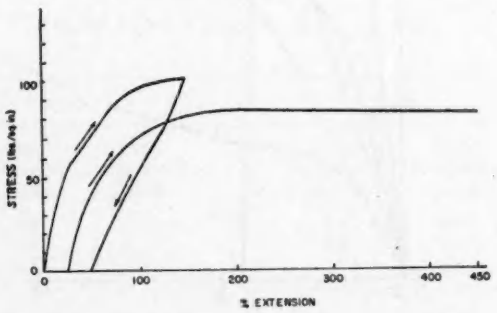

FIG. 19. *Stress-strain curve for styrene ethyl acrylate film.*

dehyde chemically react within the cellulosic fiber to cross link adjacent cellulosic chains. Probably the first to propose this theory were Cameron and Morton [5] in 1948. These authors advanced the hypothesis that wrinkle-resistant finishes for rayon are obtained through cross-bonding with thermosetting types of resins. Gagliardi and Gruntfest [10] in 1950 likewise advanced this same theory.

Treatment of cellulosic fabrics with formaldehyde will impart wrinkle resistance [10]. Golthwait [11] in 1951 suggested that formaldehyde forms a methylene bridge across adjacent cellulosic chains. Wagner and Pacsu [22] in 1952 gave added evidence that such a methylene bridge is formed when formaldehyde reacts with cellulosic fibers under highly acidic conditions.

There is little doubt that monomeric melamine and urea formaldehyde are deposited on the inside of the cellulosic fibers when applied in the normal fashion to produce wrinkle-resistant finishes. The pore size of the cotton fiber has been shown by low-temperature gas-sorption measurements to be from 16 to 20 Å in size [14]. Valko [19] has shown that the pore diameter of regenerated cellulose averages from 40 to 60 Å. Figure 21 shows a scale model of monomeric trimethylol melamine which in its extended form is 12.7 Å in length. The urea formaldehyde monomeric molecule is, of course, smaller. The melamine formaldehyde molecule is small enough to diffuse into cotton and rayon fibers. Dye-staining techniques [7] have shown that the melamine formaldehyde monomer diffuses inside the cotton or rayon fiber. In the dye-staining method, the whole fiber is dyed and then cross sectioned. The deposition of the dye in the cross section is then observed microscopically. With this technique, an acid dye (Calcocid Alizarine Blue SAPG, CI 1054), which normally does not dye a cellulosic fiber, will dye the inside of a cellulosic fiber treated with urea or melamine formaldehyde.

Monomeric melamine formaldehyde and urea formaldehyde molecules may condense with one another to form a polymer within the cellulosic fiber. Two possible ways that monomeric melamine formaldehyde can condense with itself to form polymers are shown in the next two figures. In Figure 22, trimethylol melamine is pictured as condensing with itself to form a linear dimer [24]. This condensation reaction can, of course, continue in the same manner to form a chain polymer. In Figure 23, three molecules of trimethylolmelamine are shown condensing to form a ring trimer. Further condensation in this manner is, of course, possible with the formation of a polymer of ring trimers. It can

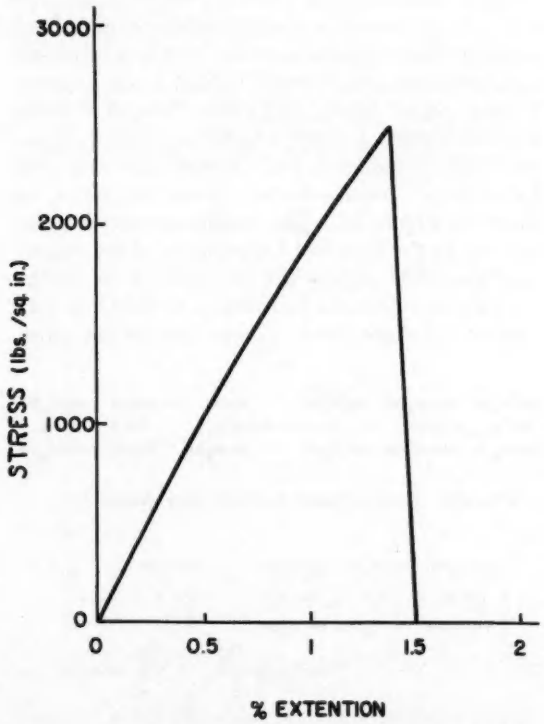

FIG. 20. *Stress-strain curve for polyvinyl acetate film.*

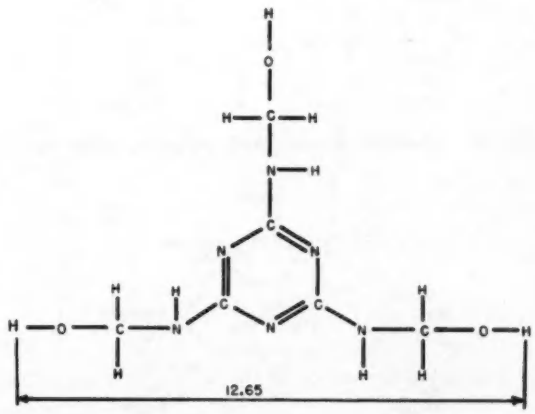

FIG. 21. *Scale model of monomeric trimethylol melamine.*

be seen that polymers of a variety of structures are possible with the condensation of melamine formaldehyde monomers to form chain or ring polymers or combinations of the two. Similar chain dimers and ring trimers, respectively, can be formed from urea formaldehyde monomers [24], as shown in Figures 24 and 25.

Wrinkle recovery can also be obtained with cellulosic fabrics by the application of low-molecular-weight polymers of melamine or urea formaldehyde. For example, a urea formaldehyde intermediate polymer consisting on the average of a pentamer, *i.e.*, 5 molecules of dimethylol urea condensed together, gave wrinkle recovery to an 80 × 80 cotton fabric. Dye-staining tests indicated that this intermediate polymer was deposited on the inside of the cotton fiber. With the application of 8% solids of this urea formaldehyde pentamer, a warp wrinkle recovery of 126° was obtained, with the untreated fabric having a wrinkle recovery of 83°.

X-Ray Diffraction Measurements

Cellulosic fibers can be characterized by X-ray diffraction measurements as being amorphous or crystalline in nature. In order for cellulose to be crystalline and give a crystalline X-ray diffraction pattern, the anhydroglucose units must be oriented in a regular and repeated fashion. Various methods of measurement have shown that native cellulose has a degree of crystallinity of 50% to 94%, whereas viscose rayon has 25% to 79% [17, 23].

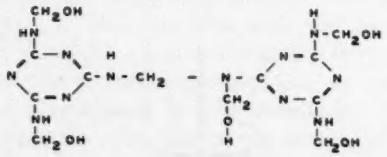

FIG. 22. *Melamine formaldehyde polymer, linear type.*

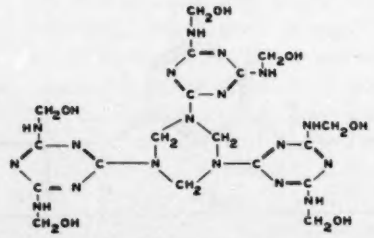

FIG. 23. *Melamine formaldehyde polymer, cyclic type.*

There is no clear-cut dividing line between the amorphous and crystalline portions of the cellulosic fiber. Rather, there is a variation from a high order to a low order of crystallinity. The amorphous regions of cellulosic fibers are believed to be more easily swollen and more reactive and accessible to reagents.

The amorphous and crystalline regions of a fiber have been pictured by Bunn [4], as shown in Figure 26. On the basis of this diagram and on the usually accepted theory that the amorphous regions are generally accessible to reagents whereas the crystalline are not, it is presumed that urea and melamine formaldehyde monomers are deposited chiefly in the amorphous regions of the cellulosic fiber. In order to obtain information on this point, X-ray diffraction measurements were made, respectively, of polymerized melamine formaldehyde and urea formaldehyde monomers. It was found that both the polymerized melamine formaldehyde and the urea formaldehyde gave, as expected, an amorphous halo but no definite X-ray diffraction pattern, as shown in Figure 27.

X-ray measurements were also made on 80 × 80 cotton fabric treated with 10% solids of methylated melamine formaldehyde monomer and urea formaldehyde monomer, respectively, as well as on a water-treated control fabric. All three X-ray diffraction patterns showed a highly crystalline cellulose *I* pattern with no evidence that the melamine and urea formaldehyde treatments had altered the lattice, as shown in Figure 28. The measurements were carried out by the Stamford Laboratories of the American Cyanamid Company and confirmed by the Southern Regional Research Laboratory of the U. S. Department of Agriculture. These data do not prove

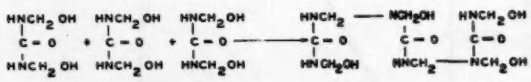

FIG. 24. *Urea formaldehyde polymer, linear type.*

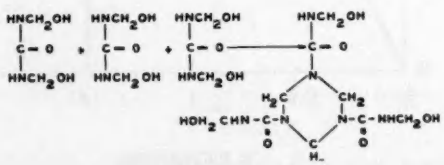

FIG. 25. *Urea formaldchyde polymer, cyclic type.*

that the melamine and urea formaldehyde are deposited in the amorphous regions of the cellulose but are in accord with this concept.

From the physical structure as well as the chemical composition of cellulosic fibers and melamine and urea formaldehyde monomers, it is obvious that chemical reaction between the cellulosic fiber and the resin monomer is a definite possibility. Figure 29 shows schematically the possibility of such a chemical reaction in which the "resin" molecule is cross-linking two adjacent cellulosic chains. In this figure, the "resin" molecule labeled MF has reacted through two of its methylol groups to form a diether, linking two adjacent cellulose chains.

Infrared Spectra

It was felt that, if chemical reaction occurred between the resin monomer and cellulose, infrared spectrophotometric measurements might reveal it. Infrared spectrophotometric measurements were made of very thin, pure, cellophane films (0.00003–0.000035 in. thick) before and after treatment with 10% of methylated melamine formaldehyde monomer. In addition, this same monomer was deposited as a film on a silver chloride plate, and infrared measurements were made. The cellophane treated with melamine formaldehyde was measured by placing the treated cellophane in front of the sample beam and water-treated cellophane in the back or reverse beam of a

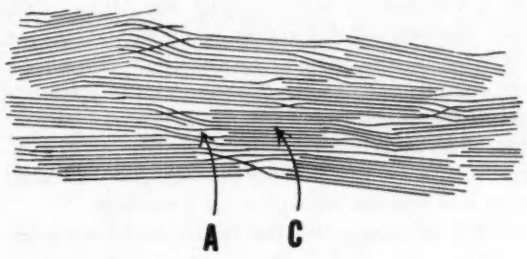

FIG. 26. *Amorphous* (A) *and crystalline* (C) *regions of fiber.*

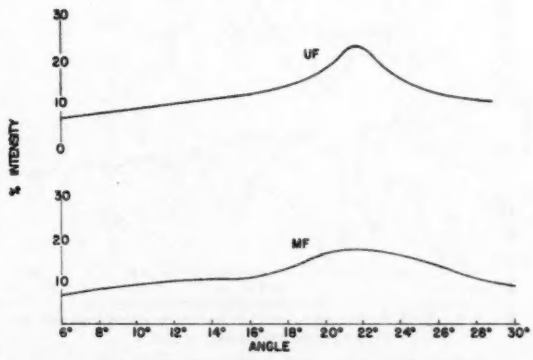

FIG. 27. *X-ray diffraction patterns of melamine formaldehyde (MF) and urea formaldehyde* (UF) *resins.*

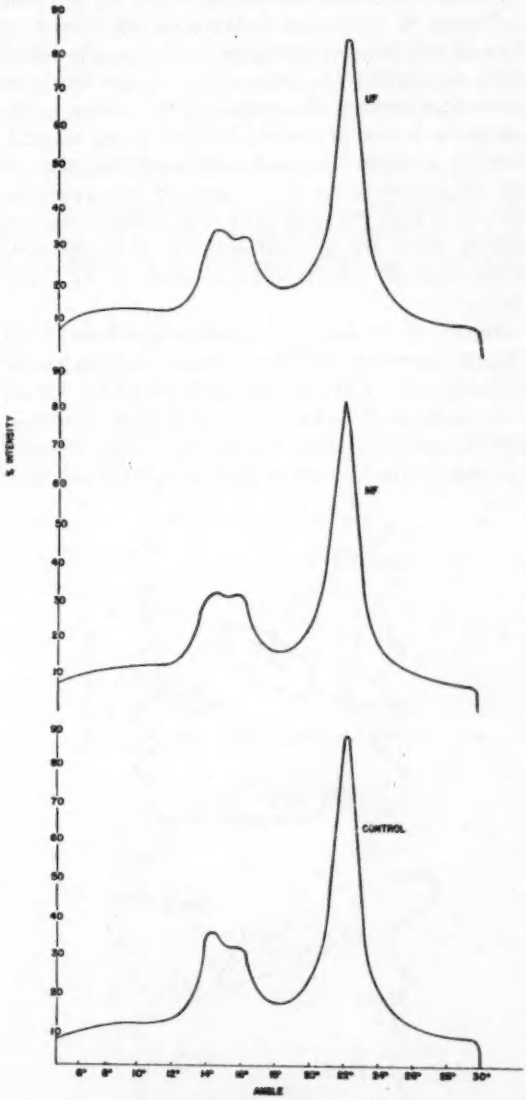

FIG. 28. *X-ray diffraction patterns of cotton fabrics treated with MF and UF, and control.*

double-beam Perkin-Elmer Model 21 infrared spectrophotometer. In this way, the cellophane absorption bands were canceled, leaving only the absorption bands of the melamine formaldehyde and any reaction product with the cellophane. The infrared curve obtained in this way was then compared with that of the melamine formaldehyde film on silver chloride to determine whether any differences occurred that might indicate a chemical reaction between the melamine formaldehyde and the cellulose.

Figure 30 shows the infrared curves from 6 to 15 μ of two films of methylated melamine formaldehyde monomer. The bottom curve gives the spectrum of an uncured film containing no catalyst. The top curve is that of a cured film containing an acid-forming catalyst. It can be observed that most of the absorption bands of the uncured are present in the cured film, the main difference between the two spectra being due to a difference in film thickness. Note especially the absorption bands at 11.1 and 10.5 μ.

Figure 31 shows the infrared curves from 10 to 13 μ of the cellophane films treated with melamine formaldehyde. This plot compares cellophane treated with methylated melamine formaldehyde monomer with no catalyst and no cure with a similar uncured melamine formaldehyde treated cellophane but with an acid-forming catalyst present. These two curves are similar, showing that the catalyst, *per se,* has no effect on the infrared spectra in this region.

Figure 32 shows a comparison from 10 to 13 μ of the following infrared curves: (1) methylated melamine formaldehyde monomer film on silver chloride with no catalyst and no cure; (2) partially cured methylated melamine formaldehyde treated cellophane with no catalyst; (3) cured methylated melamine formaldehyde treated cellophane, with a catalyst.

It will be observed that in the case of the melamine formaldehyde film on silver chloride there are two distinct absorption bands at 10.5 and 11.1 μ, respectively. The partially cured melamine formaldehyde treated cellophane shows a definite change in the relative intensity of these two bands, the 11.1 μ band becoming much greater. In the case of the cured melamine formaldehyde treated cellophane, containing a catalyst, there is an even more pronounced change. In the latter case, either a new absorption band is formed at approximately 11 μ or the 11.1 μ absorption band becomes so intense that it appears to overshadow or combine with the 10.5 μ band. The spectrum in this region is different from the spectrum of the melamine formaldehyde film on silver chloride. This change occurs in the frequency region that is associated with the C—O bond stretching. The observed spectral changes are highly suggestive of a reaction between the melamine formaldehyde and cellulose through ether formation.

It has been suggested that resins, deposited inside

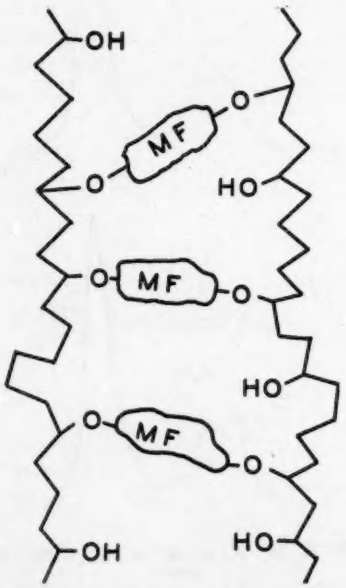

FIG. 29. *MF reaction with cellulose.*

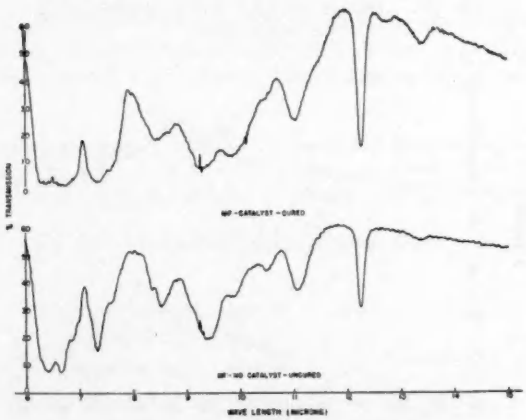

FIG. 30. *Infrared curves of MF films (cured or uncured).*

a cellulosic fiber, cross-link adjacent cellulose polymer chains by covalent bonding. Such a cross-linking process would tend to prevent the cellulose chains from slipping irreversibly past one another under the influence of an applied stress. The prevention of this irreversible slippage will reduce the permanent set of a cellulosic fiber, thereby increasing its elasticity. As demonstrated earlier in this paper, this improved single-fiber elasticity will cause fabrics made from these more elastic fibers to have improved wrinkle recovery.

Microbiological Degradation of Resin-Treated Cotton

It has been shown [7] that the treatment of cotton fabric with melamine and urea formaldehyde will prevent degradation of the fabric by cellulolytic or cellulose-destroying fungi. Melamine or urea formaldehyde treatment, however, does not prevent the growth of the surface-growing type of fungi on the fabric. These products are therefore not fungistatic. It has been shown that the acid colloid of melamine formaldehyde, which is too large to enter the cellulose fiber, does not prevent degradation of cotton by cellulolytic fungi. Neither does a polyvinyl acetate resin with a molecular weight of 20–40,000 prevent cellulosic decomposition by fungi. The fact that the application of melamine and urea formaldehyde monomers to cotton fabric does prevent growth of the cellulolytic fungi indicates the possibility of chemical reaction of these products with cellulose. In this respect, treatments of cotton fabric with melamine and urea formaldehyde monomers give results analogous to those obtained with known chemical reactions with cellulose including (1) reaction with formaldehyde, (2) acetylation of cotton, (3) cyanoethylation of cotton, and (4) phosphorylation of cotton [7].

In all these cases, resistance to cellulolytic fungi is obtained, but no resistance to the surface-growing types of fungi. Although this analogy is not proof that chemical reaction occurs between melamine and urea formaldehyde and cellulose, the data are in agreement with this postulate.

Removal of Resins from Treated Fabrics

An argument used against the hypothesis that melamine and urea formaldehyde monomers react with cellulose is the difference in the ease of hydroly-

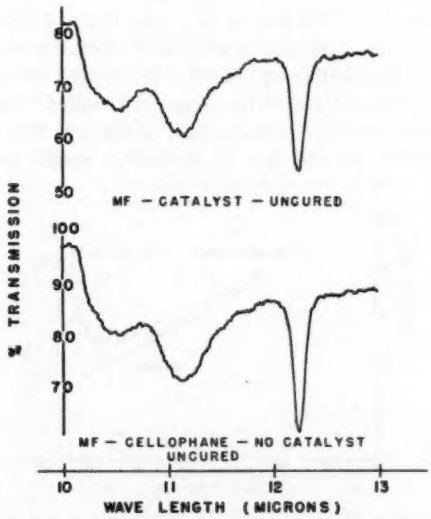

FIG. 31. *MF treated cellophane uncured (catalyst* vs. *no catalyst).*

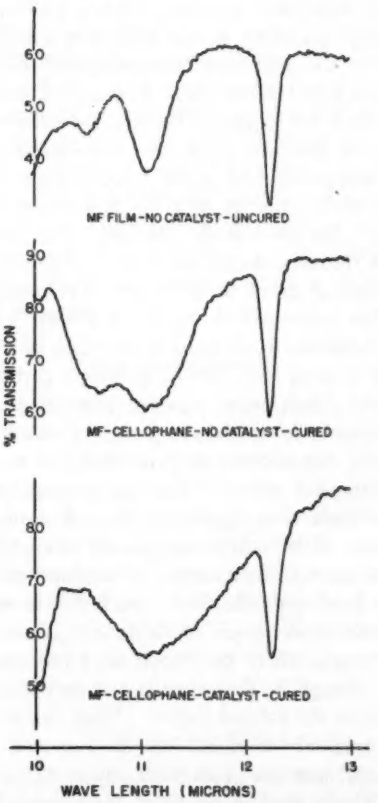
MF FILM – NO CATALYST – UNCURED
% TRANSMISSION
MF – CELLOPHANE – NO CATALYST – CURED
MF – CELLOPHANE – CATALYST – CURED
WAVE LENGTH (MICRONS)

FIG. 32. *Infrared curves of MF film* vs. *MF cellophane.*

sis between formaldehyde-treated cotton and cotton treated with melamine and urea formaldehyde. Methylene bridges are formed across adjacent cellulose chains by the reaction of formaldehyde with cotton under highly acidic conditions. Melamine and urea formaldehyde are applied to cellulosic fabrics under less acidic conditions. The melamine and urea formaldehyde can be completely removed from the fabric by acid hydrolysis. It is, however, with difficulty that formaldehyde is removed by hydrolysis under acid conditions. In order to remove the formaldehyde, it is necessary to go to such highly acidic conditions that the cellulose itself is highly degraded.

Melamine or urea formaldehyde can be removed from a treated cellulosic fabric and the properties restored to those of the untreated fabric. Figure 33 gives a plot of percent elasticity *versus* percent extension at break for 80 × 80 cotton fabric treated with methylated monomeric melamine formaldehyde. Figure 33 also gives the percent elasticity and extension-at-break curve for treated fabric from which the melamine formaldehyde has been hydrolyzed and the curve for the untreated fabric exposed to the same acid-hydrolysis conditions. The hydrolysis was accomplished by exposing the treated fabrics to the conditions that are often used commercially to remove melamine and urea formaldehyde, namely, heating for 90 min. at 85°C in an aqueous bath containing 1.5% phosphoric acid and 5% urea. The wrinkle recovery, tensile strength, and percent nitrogen values of an 80 × 80 cotton fabric treated with melamine formaldehyde before and after hydrolysis of the melamine formaldehyde are given in Table XI. As can be seen from the data, the properties of the untreated fabric were restored after hydrolysis of the melamine formaldehyde from the treated fabric.

Similar experiments were carried out on formaldehyde-treated fabric. Various concentrations of formaldehyde were applied to 80 × 80 cotton. The properties of the cloth before and after hydrolysis with the same concentrations of urea and phosphoric acid as used with the fabric treated with melamine formaldehyde are given in Table XII.

The conditions of hydrolysis used produced little, if any, change in the wrinkle recovery and tensile strength of the treated fabric. Since melamine and urea formaldehyde resins can be removed by acid hydrolysis whereas it is with great difficulty that formaldehyde can be removed from treated cotton fabric, it has been argued that the melamine and urea

TABLE XI. EFFECT OF HYDROLYSIS ON FABRIC TREATED WITH MELAMINE FORMALDEHYDE

Treatment	Wrinkle recovery Warp+Fill (degrees)	Tensile strength (lbs.)	% Nitrogen
Control	167	99	0
5.5% solids MF*	257	70	2.4
Hydrolyzed MF*	160	91	0

* Melamine formaldehyde.

formaldehyde do not react with cellulose as does the formaldehyde. Although this argument appears to have merit on the surface, on further study it does not appear to be justified. Formaldehyde is chemically quite different from melamine and urea formaldehyde. Just as it requires more highly acidic conditions for formaldehyde to react with cellulose, it might be expected that different conditions would be required to hydrolyze it from cellulose. As a matter of fact, urea formaldehyde is removed from treated cotton faster by acid hydrolysis than is melamine formaldehyde. To illustrate this point, 7.5% solids of melamine and urea formaldehyde monomers were, respectively, applied to 80 × 80 cotton fabric under the conditions previously described. The treated fabrics were then subjected to the urea and phosphoric acid hydrolysis bath described earlier. Figure 34 shows that the urea formaldehyde is removed from the fabric much faster than the melamine formaldehyde. This difference in the rate of hydrolysis is not difficult to understand since melamine formaldehyde is a different chemical from urea formaldehyde. Even though the same ether linkage may be formed between cellulose and melamine and urea formaldehyde, the rate of hydrolysis might be ex-

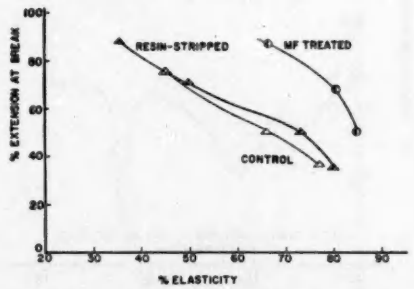

FIG. 33. *Elasticity* vs. *extension at break for MF-treated cotton fabric, and for cotton fabric from which the MF has been hydrolyzed, and control.*

TABLE XII. FORMALDEHYDE-TREATED COTTON

% Formaldehyde applied	Wrinkle recovery Warp + Fill (degrees)		Tensile strength Warp + Fill (lbs.)		% Formaldehyde content	
	Original	Hydrolyzed	Original	Hydrolyzed	Original	Hydrolyzed
Untreated	171	170	84	79	0	0
10	250	265	22	19	2.2	2.1
6	268	266	21	19	1.8	1.7
3	260	272	16	21	1.1	1.0
1½	260	250	27	17	0.6	0.9

pected to be different, just as the rate of hydrolysis of various other ethers differs, depending on the chemical groups linked to each other through the ether group.

These data show that the reaction of melamine or urea formaldehyde with cellulose to form a covalent bond is a possibility even though acid hydrolysis data might appear to indicate the contrary.

Summary

A mechanism for explaining how wrinkle recovery is imparted to cellulosic fabrics by means of melamine and urea formaldehyde has been advanced. It is postulated that the attainment of wrinkle resistance is by an increase in the elasticity of the fabrics treated with these products. It is proposed that the increase in the elasticity of the fabric is obtained by an increase in the elasticity of the fibers which is carried through to the yarns and finally to the fabric. It has been shown that the ability of a fabric to recover from creasing is more important than its ability to resist creasing. It is also proposed that the comparatively minor, but real, increase in wrinkle resistance brought about by the application of thermoplastic resins of the elastomer type to cellulosic fabrics is also caused by an increase in the elasticity of the fabric. It is suggested that the elastomeric type of thermoplastic resins imparts wrinkle resistance by an elastic type of bridging of yarn to yarn and/or by a decrease in the coefficient of friction of yarn to yarn.

The interactions possible between monomeric or partially polymerized thermosetting resins of the melamine and urea formaldehyde type within the cellulosic fiber include (1) chemical reaction between the resin and the cellulose, (2) resin formation, (3) hydrogen bonding and van der Waals forces between resin and cellulose. It is quite likely that all these interactions occur. However, it is postulated that wrinkle resistance is primarily obtained by chemical reaction within the cellulose fiber to bridge or cross-link adjacent cellulosic chains. This cross-linking prevents irreversible slippage of adjacent cellulose chains, thereby reducing permanent set. This type of chemical reaction is suggested by infrared measurements.

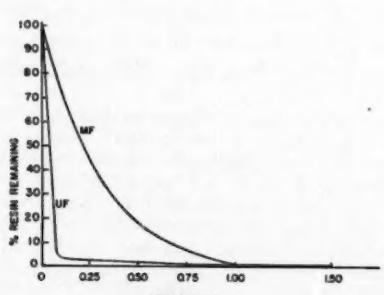

FIG. 34. *Hydrolysis of cotton fabrics treated with UF and MF.*

Acknowledgment

The authors are indebted to the American Viscose Company for furnishing the rayon fabric and yarn and very thin sheet cellophane used in this study and to the Southern Regional Research Laboratory for the X-ray diffraction measurements. They wish to express their appreciation to their many associates who contributed to this work and especially to the following: S. M. Davis, J. W. Eastes, L. A. Fluck, R. Krammes, A. L. Logan, L. J. Moretti, W. N. Nakajima, A. L. Peiker, P. B. Roth, L. A. Siegel and S. S. Slowata.

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Cotton Quality and Fiber Properties

Part II: Cavitomic Cotton*

Helmut Wakeham, Hester Stickley, and Nancy Spicer

Textile Research Institute, Princeton, N. J.

Abstract

Several years ago Hall and Elting pointed out that certain raw cottons which had been subjected to the action of fungi in the field or immediately after harvesting suffered a deterioration in cotton quality characteristics upon storage in bale form. Such cotton was termed by them to be "cavitomic." This deterioration was most manifest in a reduction of processing efficiency and a lowering of yarn quality. Certain chemical tests (pH and reducible sugars) were established as methods to detect cavitomic cotton. Because there seemed to be considerable lack of information regarding the nature and primary causes of quality deterioration attributable to cavitomic cotton, the study presented in this paper was undertaken to determine what changes in fiber properties resulting from the "cavitoma" might be responsible for the effects noted previously.

The opportunity for this study was presented when it was found that 3 of 12 bales of a homogeneous lot of Deltapine 15 cotton obtained for another investigation gave positive evidence of being cavitomic. These 3 bales were set aside, stored for a year, and then made into fabric. A similar fabric was simultaneously made from a blend of the remaining 9 bales in a processing comparison. Samples at all stages of processing were taken from both cottons and carefully compared in an extensive laboratory testing program.

It was found that the cavitomic cotton did, in fact, produce more processing waste; less even slivers, rovings, and yarns; 45% more end breakage in spinning; and yarns as much as 10% weaker than the normal cotton. In the laboratory study it was found that the cavitomic sample exhibited lower flat-bundle strength at a 5-mm. clamp spacing, a lower fiber crimp, and a shorter fiber length than the normal sample. Although the length difference was barely detectable by conventional methods it was clearly established from number-length distributions based on single-fiber length measurements.

It is concluded from this study that some of the fibers are subjected to a localized weakening as a result of the microbial action, either directly or as a result of enzymatic action during storage. These fibers break more easily in processing than fibers in the normal cotton, giving rise to a length distribution biased in the direction of short fibers. This difference in fiber-length distribution is believed to be responsible for the reduction in cotton quality characteristics observed in this and the previous work by Hall and Elting.

These results emphasize the importance of fiber-length uniformity as a factor in raw-cotton quality and the need for more sensitive methods of evaluating this factor than are presently available.

THE microbiological degradation of cotton has for many years been extensively studied in connection with the deterioration of cotton fabrics exposed to moist conditions [12]. But until recently no serious consideration has been given to the effects which such deterioration taking place in damp cotton bales during storage will have on the processing and quality characteristics of the raw cotton. Attention has now been focused on this problem by Hall and Elting, who published a series of papers [5–9] on "cavitomic" cotton, outlining various aspects of the detection and results of microbial action on cotton in the bale.

The terms "cavitoma" and "cavitomic cotton" were coined by Hall and Elting to indicate the overall effects of cotton quality deterioration during storage, which is attributable to the microbiological action. These effects were indicated to include a

* This work was performed as part of the Cotton Research Project of Textile Research Institute and supported by the following member companies: The American Thread Co., Anderson Clayton and Co., Bates Manufacturing Co., Coates and Clark, Inc., Cone Mills Corp., Dan River Mills, Deering Milliken Research Trust, Fabric Research Laboratories, Inc., Harris Research Laboratories, Joanna Cotton Mills Co., Johnson and Johnson, Inc., Pepperell Manufacturing Co., Standard Chemical Products, Inc., J. P. Stevens and Co., Inc., West Point Manufacturing Co., U. S. Rubber Co., U. S. Testing Co., Inc.

Part I appeared in the September 1954 issue.

shortening of the staple length, an increase in processing waste, a decrease in spinning efficiency, and a decrease in yarn evenness and strength. In view of these effects and because of the widespread incidence of cavitoma found by Hall and Elting, the problem would appear to have considerable economic importance and, therefore, deserves additional examination.

In the course of a comparison between irrigated and raingrown cottons being made at Textile Research Institute in its Cotton Research Project, it was found that 3 bales of an otherwise homogeneous lot of 12 raingrown bales of Deltapine 15 cotton exhibited strong signs of cavitoma when tested by Elting and Hall. These 12 bales had been carefully selected to be identical as to classer's grade, staple, character, Micronaire, and Pressley strength. The opportunity to make a careful comparison between cavitomic cotton and its undamaged counterpart thus presented itself. Check tests performed at the Institute confirmed the results of Elting and Hall. The 3 defective bales (hereafter identified by the code name "Cavitomic") were set aside to age for more than 1 year in the warehouse before opening. The remaining 9 bales (identified as "Rainmed") were opened and blended in a commercial opening line, and rebaled in low-density bales before storage to reduce any deterioration which might be taking place in them.

The subsequent processing comparison was made at Dan River Mills, Danville, Virginia, with the cooperation of the Research and Development Department personnel. Fiber, yarn, and fabric properties were measured at the Institute laboratories, at Dan River Mills, and in the laboratories of the Kendall Cotton Mills, Paw Creek, North Carolina; Johnson and Johnson, New Brunswick, New Jersey; Research and Testing Division, Cotton Branch, Production and Marketing Administration, U. S. Department of Agriculture; Development Department, Textile Division, United States Rubber Company, Winnsboro, South Carolina; and the Mohawk Mills, Amsterdam, New York.

The results of this combined effort are outlined in this paper. They confirm, in the main, the observations of Hall and Elting and demonstrate some processing and product-quality advantages which might be achieved by selecting cotton free of cavitoma. More important from the standpoint of raw-cotton quality evaluation, the results herein strongly indicate that the distribution of fiber lengths is an important quality factor. In cavitomic cotton the fibers appear to be weakened in certain places so that normal processing causes excessive fiber breakage and the production of many more short fibers than would otherwise be produced. This factor alone seems to be responsible for the inferior processing and product quality caused by cavitoma.

Identification of Cavitomic Bales

The presence of cavitomic cotton is indicated by a high pH [5, 11], a low quantity of easily soluble reducible matter (ESRM) [5], a high alkali-centrifuge value [10], and the observation with the aid of a microscope of many fibers damaged by fungus growth [5]. No one of these tests is infallible or sufficient to positively identify cavitomic bales of cotton. When the cotton is of a high pH, the presence of cavitoma may be suspected; but the cotton may be alkaline for other reasons. A very low ESRM usually indicates the activity of microflora which consume the natural sugars in the cotton; but cottons may vary considerably in this respect. The alkali-centrifuge value defined by Marsh *et al.* [10] depends on fiber fineness and, therefore, cannot be used in comparing different cottons. Practically all cottons contain spores and fungus growths to some extent, so that the microscope test is not completely satisfactory either.

Nevertheless, with respect to all of these tests, the Cavitomic sample used in the present investigation differed significantly from the normal Rainmed. (See Table I.) There is thus little doubt that the Cavitomic bales corresponded to the definitions set up by Hall and Elting when the terms were first employed.

It should be pointed out that part of the uncertainty encountered in applying tests for cavitoma to the bale is due to the localized action of the fungus. When the cotton is blended thoroughly, as when it is in roving form, the tests may be expected to give more significant answers.

TABLE I. IDENTIFICATION OF CAVITOMIC COTTON BALES

Property	Cavitomic	Rainmed
pH	8.2*	6.9†
Easily soluble reducible material (ESRM)	1.7*	4.2†
Alkali-centrifuge values (Marsh *et al.* [10])	192	185

* Based on 12 values for 3 bales.
† Based on 36 values for 9 bales.

In this connection mention should be made of a quick screening pH test employed in the Institute laboratories to spot localized cavitoma in classer's samples. The method employs a 0.1% solution of phenol red indicator containing a wetting agent. This solution when forcibly sprayed on the cotton turns fuchsia red if the cotton has a pH of 8.5 or higher. A positive test result only indicates the possibility of advanced cavitoma in the cotton, which should then be checked by other methods [7].

Processing Behavior

In the evaluation of processing characteristics the 3 Cavitomic bales and the 9 Rainmed bales, respectively, were opened, blended together, and rebaled in loose bales in one of the regular opening lines of the Riverside Division of Dan River Mills, Danville, Virginia. Two blended bales of each type were then processed through picking, carding, breaker and finisher drawing, and roving stages in the Dan River Pilot Plant of the Research and Development Department. The roving was spun into 36's warp and filling yarns at the Schoolfield Division on 6 full-sized spinning frames. Warping, winding, slashing, and weaving into an 80 × 80 print cloth were then accomplished, again in the Pilot Plant. At all stages extreme precautions were taken to treat both cotton types exactly alike and to prevent possible mix-ups. Detailed processing organization and procedures appear in *Appendix A*.

Samples were taken at all stages of processing to permit determination of fiber and fiber-assembly qualities. Wastes were collected, weighed, and analyzed. Accurate checks were made of end breakages in roving, spinning, and warping processes. Every effort was made to evaluate the processing behavior of the cottons as completely as possible. A summary of the results follows.

Processing Wastes

Percentages of opening, picking, and carding wastes for the cottons are shown in Table II. It is evident that the total opening and picking wastes of the Cavitomic cotton were more than twice those of the Rainmed sample. (The difference indicated for carding wastes is not significant.) More important is the fact that the Cavitomic opening and picking wastes contained a considerably larger fraction of lint cotton than the Rainmed wastes, according to Shirley Analyzer tests of the waste material. The full significance of this observation will be apparent after the fiber properties of the cottons have been examined.

Sliver, Roving, and Yarn Evenness

Percent size variations (based on the ratio of average range to the mean size) and mean deviations, as determined by a Uster evenness tester with linear type integrator, were determined on the 50-grain finisher drawing slivers, the 2.00 hank rovings, and the 36's yarns made from the two cotton types. The results are summarized in Table III. With the exception of sliver percent variation, the Cavitomic assemblies appear to be less even than the corresponding Rainmed ones. In the two cases

TABLE II. EFFECT OF CAVITOMA ON PROCESSING WASTES*

Source of waste	Cavitomic (%)	Rainmed (%)
Opening wastes		
Blending hoppers	0.07	0.07
Vertical opener	0.61	0.34
Lint portion	0.28	0.095
No. 1 11/12 lattice opener	0.27	0.14
Lint portion	0.037	0.013
No. 2 11/12 lattice opener	0.20	0.24
Lint portion	0.043	0.045
Total visible waste	1.15	0.75
Lint portion	0.360	0.153
Total invisible waste	1.33	0.41
Total opening waste	2.48	1.16
Picker waste	1.07	0.43
Card waste (strips, sweeps, and white wastes)	6.87	6.61

* All waste percentages have been corrected for differences in moisture contents occurring at the time of processing.

TABLE III. EFFECT OF CAVITOMA ON EVENNESS

Stocks and Test	Cavitomic (%)	Rainmed (%)	No. samples tested for each cotton
50-grain finisher drawing			
RUE*	20.79	21.45	16
LUE†	4.67	3.79	16
2.00 hank roving			
RUE*	46.55	44.32	12
LUE†	8.42	8.28	12
36's carded yarn			
LUE†	19.44	18.62	72

* Range unevenness as obtained from the Uster chart.

† Linear unevenness as obtained from the Uster linear integrator.

indicated by asterisks, the differences are statistically significant at the 5% level for the number of measurements made. While all the differences are fairly small, there is little reason to doubt that the Rainmed cotton is superior to the Cavitomic with respect to evenness. How important these small differences are to processing performance and product quality is not known.

Spinning Efficiencies

A spinning test involving 28,870 spindle hours for each cotton type was performed to determine the spinning efficiencies of the Cavitomic and Rainmed samples. In this test the rovings were distributed in a statistical pattern over 6 full-sized spinning frames. A check of end breakages by spindle was kept for 72 hrs. The roving positions were shifted twice to different frames during the test to reduce the effects of any possible roving by spindle or frame interactions which might be occurring. Details of the spinning test and analysis of the results are found in *Appendix B*.

The results of this test, which are shown in Figure 1, show an average of 45% more spinning end breaks for the Cavitomic than for the Rainmed sample. At the lower twist multiple the breakage rate for Cavitomic was 55% higher. Since the work load of a spinner is determined mainly by the end-breakage rate, the increased spinning costs arising from the use of cavitomic cotton are quite apparent from this test.

Yarn Strengths and Elongations

Mention has already been made of the effect of cavitoma on yarn evenness (Table III). Skein-strength determinations and measurements of single-end strengths and elongations were also made. The results of these tests show the Rainmed yarns to be about 10% stronger than the Cavitomic yarns. (See Table IV.) Rainmed yarn elongation to break averages 5% higher than the corresponding value for Cavitomic yarns. This result would be expected since for such similar cottons and yarns elongations are directly related to strength values.

Fabric Properties

The Cavitomic and Rainmed 36's yarns were woven into an 80 × 80 fabric which was then mercerized, bleached, dyed, and resin finished, using commercial procedures throughout. Samples of fabric were taken at each stage. Various properties of the fabrics were measured in an effort to determine any differences which might be ascribed to the cavitoma. Details of the fabric treatments and of the test methods will appear in a later paper in this series, describing the differences between the rain-grown and irrigated cottons mentioned earlier.

In the present study only minor differences between the Cavitomic and Rainmed fabrics were observed. The Cavitomic fabrics showed a slightly lower strength in the warp direction only. They were also somewhat less permeable (approximately 10%) to the passage of air than the Rainmed fabrics, according to measurements on both the Gurley and Frazier instruments. Upon autoclaving, the Cavitomic bleached fabric yellowed more than the Rainmed, although the former was less yellow than the latter before treatment. The light-blue-dyed fabrics, both mercerized and unmercerized, showed a barely perceptible difference in color, the Rainmed controls being very slightly darker in shade than the Cavitomic. These differences were confirmed with tristimulus color difference calculations based on measurements with a G.E. Spectrophotometer at the laboratory of the Mohawk Carpet Mills. Thus, on the whole, it seems that the small differences between Cavitomic and Rainmed yarns were lost in the fabrics.

It would appear, then, that the main disadvantage in using cavitomic cotton is in reduced processing efficiency with the production of somewhat inferior quality yarns. Although no weaving efficiencies were determined, it would not be surprising if the

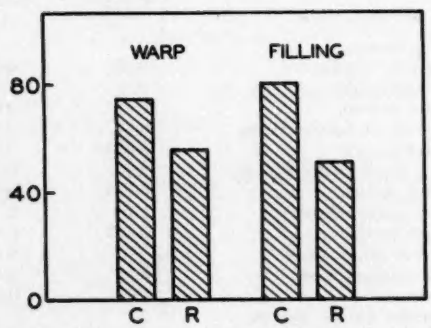

FIG. 1. *Spinning end-breakage per 1000 spindle hours for 36's warp and filling yarns of Cavitomic and Rainmed cotton.*

decrease in yarn strength and evenness was reflected in an increase in loom stoppages.

Fiber Properties

Because the Cavitomic and Rainmed bales were originally carefully selected and purchased to meet the same grade, staple, and fineness specifications, differences in these characteristics were not readily discernible. For this reason careful measurements were made of other fiber properties in an attempt to discover the reasons for the processing differences indicated above.

Fiber Length

Both length array and Fibrograph [1] results indicated the raw Cavitomic sample to average about $\frac{1}{32}$ in. shorter than the normal Rainmed. (See Table V.) This difference in average length values was reflected in the weight-length distribution from the length array by a slight shift of the distribution peak in the direction of lower fiber length.

Because length distributions have been found to be significant factors in the processing behavior of other cottons, single-fiber length measurements were made on bale and card-sliver fibers for both cottons studied here. The instrument used was a TRI modification of the Wool Industries Research Association Fiber Length Tester [2]. This machine measures fibers as short as 0.2 in. and automatically transmits the length information onto an IBM punched card. Fibers shorter than 0.2 in. were registered manually. The average lengths obtained by this method for the two cottons differed by 0.1 in. (Table V). Number-length distributions are plotted in Figure 2. These results demonstrate a considerable difference in length properties between the Rainmed and Cavitomic samples.

TABLE IV. EFFECT OF CAVITOMA ON STRENGTH AND ELONGATION OF 36's CARDED YARNS

Property	Cavitomic	Rainmed
Skein break (CSP)	1942	2101
Single-end strength (g.)*		
2-in. gage		
Warp	261	273
Filling	225	250
20-in. gage		
Warp	214	233
Filling	193	217
Single-end elongation (%)*		
2-in. gage		
Warp	6.96	7.10
Filling	6.27	6.74
20-in. gage		
Warp	5.29	5.48
Filling	4.84	5.20

* Each property value is based on 180 breaks.

Fineness and Maturity

Extensive tests showed these two cottons to be identical in fiber size and maturity.

Bundle Strength

Conventional Pressley tests on fibers from classer's samples showed a slightly higher bundle strength for the Cavitomic cotton than for the Rainmed (Table V). A careful check of blended composite bale samples failed to confirm this difference and, in fact, revealed that at the 5-mm. clamp spacing the Rainmed

TABLE V. FIBER PROPERTIES

Raw-Cotton Quality	Cavitomic	Rainmed
Grade (official standards)	M-Br	M-Br
Staple length (in.)	$1\frac{1}{16}$	$1\frac{1}{16}$
Fiber length		
Length-fineness array		
Upper-quartile length (in.)	1.191	1.225
Mean length (in.)	0.968	0.985
Coef. of variation (%)	32	33
Fibrograph		
Upper-half mean (in.)	1.08	1.12
Mean (in.)	0.82	0.86
Uniformity ratio (%)	76	77
Number-length averages		
Bale	0.70	0.80
Card sliver	0.66	0.77
Fiber fineness		
Length-fineness array	4.24	4.26
Micronaire	4.34	4.30
Caustic swelling maturity (%)	80	79
Flat-bundle strengths		
Conventional Pressley test (0 gage, 1000's p.s.i.)		
Lab. A	84.7	83.7
Lab. B	85.9	83.0
Instron-Pressley-TRI test (g./grex)		
0 gage		
Bale	3.89	3.92
Roving	3.89	3.89
1.5-mm. gage		
Bale	2.48	2.49
Roving	2.61	2.70
5-mm. gage		
Bale	1.62	1.69
Roving	1.85	1.89
Nickerson-Hunter colorimeter color of blended lint ($Rd/+b$)	76.4/9.1	77.2/9.8
Alkali-centrifuge values		
Bale	192.3	184.9
Roving	199.9	199.3

fiber bundles were about 4% stronger than the Cavitomic bundles.

Color

Nickerson-Hunter cotton colorimeter measurements of the raw cottons showed them to be equal in reflectance values (*Rd*) but different in yellowness factors, the Rainmed being the more yellow of the two. It is interesting to note that this difference in color persisted even through to the bleached fabrics. After the fabrics were mercerized, the difference was no longer observable.

Alkali-Centrifuge Values

Bale and roving samples of the cottons were tested for fiber surface damage by the method of Marsh, Merola, and Simpson [10] in which the pickup of caustic by the fibers is measured. Since the cottons are of the same fineness and maturity, a difference in their "alkali-centrifuge" value implies a difference in penetration of the outer fiber walls and swelling of the fiber by the caustic solution. Damage to the fibers in processing, for example, will cause an increase in caustic absorption of the cotton. The results in Table V show a pronounced difference between the cottons, especially for the bale samples.

Single Fiber Properties

Single fibers from roving of each cotton were tested for their mechanical properties. Two operators, working in parallel, each selected 48 fibers at random from different places on 4 roving bobbins for each cotton for a total of 192 fibers. Testing was done on the Instron tensile tester equipped with vibroscope and integrator, employing procedures previously described [14]. From the results, which are summarized in Table VI, it can be seen that the cottons differ only with respect to the energy to uncrimp the fibers. The smaller difference in average elongations to break is not statistically significant.

Fibers broken in this test were classified with respect to whether the break occurred *at* or *between* structural reversals [13]. It was observed that only 37% of the Cavitomic fibers broke *at* reversals, whereas the corresponding value for Rainmed was 45%. Since the fiber in tension breaks at its weakest point, and since only a small fraction of the fiber length is taken up by the reversals, a chance localized weakening of the fiber, such as that which might be expected by microbial activity, would be expected to occur between the reversals. The fraction of breaks involving reversals would in this case be lower. The observation of this effect thus gives evidence that the Cavitomic fibers are preferentially weakened in localized regions along the fiber axis.

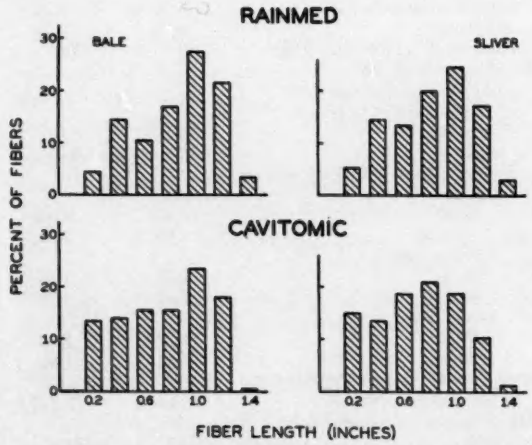

FIG. 2. *Number-length distributions of cotton fibers in Cavitomic and Rainmed bale and card-sliver samples.*

Properties of Fiber Assemblies

Rovings

The strength and stiffness (force-extension slope) of 2.00 hank rovings were measured in this study as a test of cooperative behavior [4]. It has been observed in the past, for example, that in general stronger and stiffer rovings give better spinning performance. Roving properties, of course, are not uniquely determined by fiber properties, but depend

TABLE VI. PROPERTY VALUES OF SINGLE FIBERS TAKEN FROM ROVING *

Property and Units	Rainmed	Cavitomic
Area of cross section ($\times 10^{-6}$ cm.^{2})	1.256	1.236
Breaking load (g.)	4.63	4.64
Elongation to break (%)	8.50	8.00
Hookean slope (g./%)	0.592	0.604
Crimp energy ($\times 10^{-3}$ g. cm./cm.)	1.31	1.06
Energy to break ($\times 10^{-3}$ g. cm./cm.)	190	187
Elastic modulus ($\times 10^6$ g. cm.^{2} for 1% ext.)	0.505	0.498
Breaking stress ($\times 10^6$ g./cm.^{2})	3.85	3.78

* Test conditions: Instron tensile tester with vibroscope attachment; 0.5 in. fiber gage length; 0.05 in./min. crosshead speed; 10 in./min. chart speed; 10 g. full-scale load; 70°F; 65% R.H..

also to a great extent on the roving geometry. This fact must be kept in mind when one draws conclusions about fiber behavior from measurements on rovings.

In this research the rovings were carefully controlled so that differences in roving behavior would be indicative of differences in fiber properties. All processing through roving was done in parallel or series through the same machines so that the two rovings were the result of identical processing. Since roving behavior is sensitive to twist, careful twist counts were made to give assurance that the Cavitomic and Rainmed rovings would be the same in this respect.

Mechanical properties were determined on the twisted and relaxed rovings one day (fresh) and 61 days (aged) after their manufacture (Table VII). Relaxation consisted of hanging a length of the roving for about 3 hrs. and allowing the twist to come out. The rovings were "aged" on the bobbins in a conditioned room. In all cases both the strength and stiffness of the Rainmed rovings were higher than those of the Cavitomic. These differences are most probably due to the difference already noted in fiber length between the cottons. If all other fiber properties were equal, the cotton with greater crimp would be expected to produce roving with higher breaking strength but lower stiffness than cotton of lower crimp energy.

Yarn Twist Multiple vs. *Strength*

Both Cavitomic and Rainmed were spun into 36's yarns at various twist multipliers which were tested to determine the relation between yarn strength and twist multiple for each cotton. The results are depicted in Figure 3. Although the maximum yarn strength obtainable from these cottons was about equal, considerably more twist was required for the Cavitomic sample for optimum strength than for the Rainmed.

TABLE VII. MECHANICAL PROPERTIES OF ROVINGS *

Property	Cavitomic	Rainmed
Strength (g.)		
Twisted†		
Fresh‡	88.7	101.3
Aged 61 days‡	97.6	120.8
Relaxed†		
Fresh	10.1	11.8
Aged 61 days	35.5	42.3
Stiffness (g./% extension)		
Twisted		
Fresh	75.4	84.8
Aged 61 days	81.9	96.1
Relaxed		
Fresh	5.6	6.8
Aged 61 days	34.5	43.7

* Mean values based on 20 measurements.

† Twisted roving was tested as it came from the bobbin; relaxed roving was allowed to untwist by hanging free for 3 hrs.

‡ Fresh roving was tested within 24 hrs. after manufacture; aged roving was kept in a conditioned room on the bobbin the indicated number of days.

Discussion and Conclusions

The cotton sample in this investigation labeled as Cavitomic corresponds to that described by Elting and coworkers in two major respects. In the first place the raw stock exhibited higher pH, lower reducing values, and higher alkali-centrifuge values than the normal Rainmed counterpart. Second, the Cavitomic sample in processing exhibited increased processing waste, less even slivers, rovings, and yarns, less efficient spinning, and weaker yarns than the Rainmed sample. Thus there is little doubt that the sample so labeled is, in fact, a cavitomic cotton in every sense of the definition for such a cotton. The differences in fiber properties between the Cavitomic sample and the Rainmed sample might then be expected to give reliable indications regarding causes for the reduction of cotton quality by cavitoma.

What are these differences in fiber properties? There are only three which appear to be important: a lower Pressley bundle strength at a wide clamp

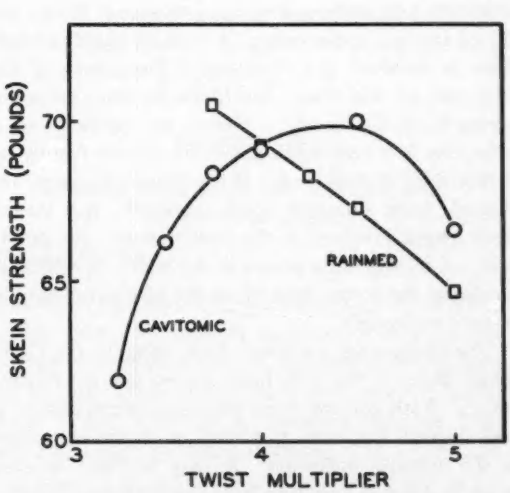

FIG. 3. *Relation between skein strength and twist multiplier for 36's yarns of Cavitomic and Rainmed cottons.*

spacing, a lower fiber crimp, and a shorter fiber length for the Cavitomic sample.

The strength values obtained in the various tests are somewhat conflicting. Conventional Pressley bundle tests performed in the commercial laboratories seemed to give a slightly higher strength for the Cavitomic bale samples. Hall and Elting [7, 8], on the other hand, reported no consistent difference in flat-bundle strength between cavitomic and normal cottons. This observation was confirmed in the TRI laboratory tests made at close spacings of the bundle clamps. The measurements at the 5-mm. spacing, however, showed a definitely lower strength for the Cavitomic sample. This strength difference was found even for fibers from the roving, in which many of the weaker fibers were probably removed or broken in earlier processing steps. The single-fiber tests of roving fibers, however, showed no strength difference between the cottons although there was a difference in the preferred breaking location.

These results are consistent with the picture of a localized weakening of some of the fibers as a result of the microbial action. Such a weakening would be very difficult to detect in a series of single fiber tests unless many fibers were tested. Furthermore, since the single test was made on roving fibers where a good representative selection is obtainable, at least some of the weaker fibers present in the bale were no longer available for test. Hence, the single-fiber strength test would not necessarily show a strength loss for the Cavitomic sample. In the conventional Pressley test, although several thousand fibers are tested in the bundle, only a very short length of each fiber is involved and, because of the nature of the test, not all the fibers contribute to the maximum strength of the bundle. Hence, the presence of a relatively few very weak places would not readily be detected by this method. If the Pressley clamps are spaced some distance apart, however, the longer fiber length involved in the test increases the possibility of testing weak places in the fiber. Under this condition the lower strength of the Cavitomic sample is very noticeable.

The reasons for the lower fiber crimp of the Cavitomic fibers in the 2.00 hank roving are not understood. Both cottons were processed simultaneously and through the same machines, with the exception of the opening operation. It may be that, because of enzyme action resulting from the microbial growth, the Cavitomic fibers are more susceptible to permanent straightening in the mechanical manipulation connected with ginning and subsequent processing than the Rainmed fibers are.

The effects of this difference in fiber crimp, however, are such that they tend to cover up the observed differences in other fiber properties and processing behavior. Previous experience in the TRI laboratory has shown that cotton fibers exhibit higher flat-bundle strengths when their crimp has been decreased by drawing or combing. Apparently the experienced Pressley operator is able to make a more uniform, stronger bundle if the cotton fibers require less energy to uncrimp. This observation may explain the higher Pressley strengths observed in the conventional test. If this effect is correct, the difference in actual corrected strength between the Cavitomic and Rainmed samples at the 5-mm. clamp spacing may be even greater than that shown in Table V.

It has also been shown in connection with other processing studies that more efficient spinning is obtained with fibers of lower crimp energy, other fiber properties being equal. Here the Cavitomic cotton spun much less well than the Rainmed despite the greater crimp energy of the latter. In this case, however, the fiber-length distributions of the two cottons were quite different from each other, as has been noted. It is reasonable to conclude from this that the fiber-length difference between the cottons exerts a more profound effect on processing performance and yarn quality than the crimp difference.

The effects which fiber length and length distribution may have on such yarn properties as strength, strength variation, and size uniformity have been recognized since the early studies by W. L. Balls [3]. It is for this reason that length-measuring methods such as those employing the Suter-Webb cotton fiber sorter and the Fibrograph also attempt to evaluate length uniformity of the cotton sample. These methods, however, yield weight-length distributions in which the presence of a large number of short fibers in the sample may be easily overlooked. Yet it is evident from this work and many other considerations that the processing efficiency and yarn quality of a cotton sample is very sensitive to the presence of short fibers. There seems little doubt that, in this case at least, the inferior performance of the Cavitomic sample as compared to the Rainmed is directly attributable to the many more short fibers in the former.

This investigation thus emphasizes the need for a rapid and sensitive method of evaluating fiber-length distribution in raw cotton.

Appendix A

Processing Organization and Procedures

Six bales of cotton were processed together, 2 bales each of Cavitomic and Rainmed, and another 2-bale lot of an irrigated cotton which was compared to the Rainmed. Opening and spinning of the cottons were performed in production areas of Dan River Mills, while the operations of picking through roving and weaving were performed at the Dan River Mills Pilot Plant. Bleaching, dyeing, and finishing of the fabrics were done at Pepperell Manufacturing Company at Pepperell, Alabama. All processing was under constant supervision by laboratory personnel.

The cottons were opened, cleaned, and rebaled on an opening line consisting of six Saco-Lowell No. 7 feeders, one vertical opener, two 11-over-12 lattice openers, and one Lummis bale press. The insides of the bales were sampled and tested for moisture content with the Hart Moisture Meter. The opening line was cleaned out after each lot of cotton, and the wastes were weighed and sampled.

In the Pilot Plant, the cleaned bales were opened in a Kitson preparer before picking with one Saco-Lowell type R-6 picker with single Kirschner beater and blending reserve. The stock was passed through the picker twice, two breaker laps being fed to produce 50-yd. finisher laps weighing 14 oz./yd. In this and subsequent processing through spinning, the three 2-bale lots were handled as 6 independent cottons. Hart Moisture Meter readings were taken. Both wastes and picker laps were weighed and sampled.

Three Whitin revolving flat cards were used to produce 50-grain carded sliver. Cotton from one bale was processed on all three cards simultaneously; the cottons were changed in random order after every two laps. At each change of cotton the cards were stripped and cleaned out, and the wastes were weighed and sampled. During processing, layers of carded sliver from each card were taken as samples for fiber and assembly tests. Moisture-content values were also taken at the time of sampling.

The cottons were processed through two Saco-Lowell conventional 4-roll, 4-delivery drawing frames with synthetic covered top rolls into 50-grain finisher drawing sliver through 50-grain breaker drawing sliver. Six doublings were used in both drawing operations. Care was taken in creeling to distribute evenly the cans of sliver from different cards or breaker drawing deliveries. Moisture-content readings were made, and samples of sliver were taken for fiber and assembly tests.

All the cottons were processed into 2.00 hank roving in parallel on one Saco-Lowell 10 × 5 J3 roving frame equipped with revolving clearers. The 84 spindles on the frame were divided into six 14-spindle groups, and each group was randomly assigned one bale. Twice during the operation the cottons were reversed on the frame so that each group of spindles carried a different cotton type for one-third of the test. During each time period samples were taken and moisture-content readings were made.

The spinning test is described in *Appendix B*.

After spinning, the yarns from the two bales of each cotton type were combined. The warp yarns were wound on tubes and put up on loom beams after warping and slashing. The filling yarns were rewound on filling bobbins. The cottons were each woven into an 80 × 80 print cloth using six Crompton and Knowles automatic looms.

Approximately 400 yds. of fabric of each of the test cottons were sent to Pepperell Manufacturing Company in Pepperell, Alabama, for wet processing. After desizing and washing, half the goods was mercerized; then all the fabric was bleached and dyed a medium-blue shade. Samples from each piece of fabric were taken for testing.

Appendix B

Spinning Test Methods, Results, and Analysis of Data

Spinning Machinery

Six Saco-Lowell spinning frames with Roth SR-1 drafting and 216 spindles each were used in the spinning test. These were in the regular production area at Dan River Mills. Ring size was 1¾ inch; spindle speed 9329 r.p.m.; traveler number 3/0; front roll speed for warp spinning 115 r.p.m. and 134 r.p.m. for filling. Three frames were set up for warp (T.M. 4.25) and three for filling twist (T.M. 3.75). Roving count was 2.00 hank.

Spinning Operation

Each side of each frame was divided into 6 groups of 18 spindles. Each group was assigned to spin roving from one of the six bales in the test. After one-third of the test all the roving bobbins were shifted, and again after the second third, so that each spindle ran each of the three cottons in the test for one-third of the time. Room conditions ranged between 82–92°F and 53–55% R.H. Moisture in the cotton averaged 5.3% for all cottons. The spinning test was conducted on a three-shift basis for 3 successive days and was under continuous supervision by laboratory personnel. The same checkers were used throughout the test. Spindle hours totalled 27,870 per cotton.

Analysis of Variance of Spinning End-Breakage Results

Since cottons were the only variable considered complete in this analysis the cotton effect was tested against the significant variance of the cotton-by-frames interaction. $F_{0.99}$ (2, 10) is 7.65; hence the cotton effect is significant at about the 1% level.

Source of variance	Degrees of freedom	Sums of squares	Mean squares	*F*
Between cottons	2	176	88.0	7.15
Between shifts	8	130	16.2	1.59
Between frames	5	99	19.8	4.30
Cottons and shifts interaction	16	78	4.9	1.00
Cottons and frames interaction	10	123	12.3	2.67
Shifts and frames interaction	40	406	10.2	2.22
Cottons, shifts, frames interaction	80	391	4.9	1.07
Residual	486	2249	4.6	
Totals	647	3652		

Spinning End-Breakage Rates

Differences between cottons and variations between spinning frames are illustrated by the average number of end breaks per 1000 spindle hours shown below.

Warp yarns were made on frames 1–3, filling yarns on 4–6. Part of the difference between frames must be ascribed to differences between warp and filling twists.

Frame number	Cavitomic	Rainmed
1	59.17	54.81
2	63.11	44.49
3	62.77	40.15
4	83.29	39.77
5	58.07	53.15
6	91.44	56.07
Mean rate	69.64	48.01

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Cotton Quality and Fiber Properties

Part III: Effects of Drying at High Temperatures Prior to Ginning*

Donald J. Leitgeb† and Helmut Wakeham‡

Textile Research Institute, Princeton, New Jersey

Abstract

The increased use of drying and cleaning equipment at cotton gins has occasioned complaints from spinners that the "quality" characteristics of cottons are being lowered due to "overdrying" of the seed cotton prior to ginning. The present study was undertaken to clarify the effects of overdrying on the processing characteristics of cotton and to determine any changes in fiber properties relating thereto.

Three 2-bale lots of cotton were prepared from a homogeneous batch of hand-picked seed cotton by drying in three parts before ginning. The first part was passed through the driers with unheated air. For the second part the air in the first drying tower was heated to 450°F; the air in the second tower was unheated. For the third part the air in both drying towers was heated to temperatures between 170° and 290°F. Both heated cottons were dried to 3.8% moisture in the lint, well below the recommended minimum of 5%. The cottons were evaluated by means of a small preliminary spinning trial and a full-scale processing trial. Samples taken during the trials were studied to determine the properties of the fibers and the fiber assemblies.

The greatest processing difference between the cottons was in the spinning end-breakage rates, which increased as much as 21.4% due to excessive drying for the high-temperature-dried sample. The yarns showed a decrease in strength, evenness, and yarn-appearance grade for the heated cottons, with similar results for roving samples. Raw-cotton samples exhibited only minor differences in fiber properties when examined by conventional methods. Alkali-centrifuge values indicated significant fiber surface damage with heating; and there was evidence to indicate a greater crystallinity for the heated cottons. Tests for the fiber number-length distributions showed that both before and especially after processing through roving the excessively dried cottons consisted of more short and fewer long fibers than the control cotton. It is believed that the presence of many short fibers is the main cause of processing difficulties and reduced yarn quality.

Introduction

In recent years many spinners have complained about the inferior quality of cotton which has been heated and "overdried" prior to ginning. Although the specific causes and results of this inferior quality have heretofore never been clearly determined, most experienced spinners agree that the "overdrying" gives rise to processing difficulties and low yarn quality. Inasmuch as a considerable fraction of the United States cotton crop is processed through gins equipped with driers [10], it is important to know more about the effects of overdrying on cotton quality.

Seed cotton as it comes to the gin contains a considerable amount of foreign matter (leaves, bracts, stems, soil, etc.), especially if it is mechanically harvested. The quantity of this material in the ginned cotton determines the grade and, for below middling

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† Textile Engineer.
‡ Associate Director of Research.

grades to a large extent, the price of the cotton. It has been found that the removal of this foreign matter is greatly facilitated by drying the seed cotton before it is introduced into the pre-gin cleaners and the gin stand itself. Since the seed cotton coming to the gin may vary considerably in moisture content, since the temperature of the drying air at the gin is usually not well controlled, and since the farmer and ginner are intent on producing the highest possible grade of cotton, it is possible that on occasions the cotton fibers may be heated to a temperature high enough to produce slight discoloration and dried to well below the recommended minimum of 5% moisture content [15].

It has not been clear whether the reduction in cotton quality accompanying the drying operation at the gin results from the effects of high temperatures on the fiber properties, from a reduction to too low a moisture content, from the ginning of the cotton while it is dry, or from a combination of these factors. It is believed that the method of drying cotton affects the properties of the fibers and that the changes produced in the initial drying of the fibers on the cotton seed are more pronounced than those resulting from subsequent drying cycles [2]. Furthermore, dry cotton fibers exhibit different physical properties from wet ones, *e.g.*, are stiffer, more brittle, and weaker [7]. The specific mechanism, however, whereby the drying operation results in a depreciation of cotton quality as recognized by the yarn and fabric manufacturer is not well understood.

Accordingly, Textile Research Institute undertook a study of overdrying at the gin with the following objectives: (1) to establish the nature of the effects which the deterioration of raw-cotton quality by overdrying has on processing performance and yarn quality, and (2) to determine the factors contributing to this deterioration. In this study it was felt necessary to set up a series of ginned samples in such a way that no factors other than drier temperature and moisture content could be responsible for the mill-processing behavior of the samples. It was also felt that the samples would have to be processed in a commercial manner to establish any differences found as being typical of those causing the complaints of the spinners. Finally, it was necessary to make a thorough study of the cotton fiber properties to determine what characteristics of the fibers might give rise to these differences in processing behavior. It was hoped that this last phase of the study would lead to means of identifying samples which had been excessively dried at the gin.

The Samples

Seed cotton for 6 bales of Deltapine 15 were hand picked in 1 day from the same field on the Nugent Farm of the Delta and Pine Land Company near Greenville, Mississippi. Bags from the pickers were distributed systematically among three wagons so that each of the 2-bale lots would be homogeneous and equivalent to the others. The day was cloudy with a few light rain sprinkles on the cotton field. The moisture of the seed cotton was about 10%, sufficiently high to require a drying treatment.

Ginning was performed at the U. S. Department of Agriculture ginning laboratory at Stoneville, Mississipi. The gin was so arranged that by means of suitable gates and by-passes the seed cotton only passed through two drying towers, a distributor, and two-unit Mitchell feeders before dropping into the gin. Thus, the usual pre-gin cleaning or machining, which may also reduce cotton quality, was omitted so that any differences between the cottons could be directly attributed to the hot-air drying.

The cotton was ginned on the day after picking. During the night the weather had changed and the relative humidity of the atmosphere was decreased to about 50%. The cotton of the first 2 bales which was blown through the drying towers with unheated atmospheric air therefore had its moisture level reduced to about 6% as it entered the gin stand. Two more bales were ginned after drying with 250°F air temperatures in both drying towers, and the final 2 bales with the air in the first drying tower at 450°F and with no heat in the second. These three lots will be identified by the code words "Ginwet," "Ginmild," and "Ginhot," respectively. Both heated cottons were dried to a moisture content of 3.8%. The ginning data appear in *Appendix A*.

In the evaluation of these lots of cotton three series of tests were performed. Samples of the cottons were submitted to the Clemson Cotton Testing Laboratory of the U. S. Department of Agriculture for a preliminary spinning trial. A full-scale processing trial was conducted at Joanna Cotton Mills Company to compare the processing characteristics of the cottons and to obtain representative samples for laboratory tests. Finally, samples of fiber, sliver, roving, and yarn were studied at Textile Research

Institute to determine any differences which might account for the results of the processing trials. In the interest of brevity the above organizations will hereinafter be referred to as Clemson, Joanna, and TRI.

As a result of these studies it was found that excessive drying of the cotton at the gin produces detectable changes in cotton-fiber properties which are reflected in reduction of the cotton quality and processing efficiency. The present paper outlines the experiments and processing trials performed to establish the magnitude of these changes for the samples described above.

Processing Behavior

Preliminary Processing Trial at Clemson Cotton Laboratory of U. S. Department of Agriculture

Approximately 30 lbs. of each of the three seed cottons were taken out of the gin stands prior to ginning to set up a secondary experiment to determine the effects of preconditioning the cotton to a common moisture-content level before ginning. Half of each sample was ginned immediately on a laboratory 20-saw gin, and the other half was allowed to condition for 20 days before being ginned on the same 20-saw gin. Quantities of these samples were submitted to Clemson for a preliminary spinning trial in which carded 36/1 and 50/1 yarns were made [14]. In brief, the processing procedure included opening by hand, two processes of picking, carding, two processes of drawing, one superdraft roving process, and double-creel long-draft spinning.

This preliminary test (Clemson Laboratory Test No. C-2113) showed slightly more waste for the heated samples than for the Ginwet control. Nep counts and spinning end breakage were considered low for all cottons. No appreciable differences due to preconditioning before ginning were observed.

Full-Scale Processing into Carded 41/1 Filling Yarn at Joanna Cotton Mills Company

It was decided to determine whether any processing difficulties encountered with the heated cottons would be alleviated by conditioning to a higher moisture level before processing. Ten days prior to the trial, 1 of the 2 bales in each ginning lot was therefore separated into halves and fluffed to allow for better air penetration and moisture absorption. However, the increase in moisture content of the opened bales over the unopened bales was so small that no differences between them were observed during processing. Therefore no distinction is made here.

All processing was done in the production areas of Joanna Cotton Mills under constant supervision by laboratory personnel. The cottons, while being handled as 6 separate bales, were processed simultaneously and under comparable conditions so far as was practicable. They were processed in series in a random order in all operations through drawing. (Processing organization is summarized in *Appendix B.*) In roving, 1 frame was divided into 6 equal groups of spindles, and 1 bale was assigned to each group. Twice during the roving operation the sliver cans were rearranged so that each group of roving spindles carried a cotton from each of the ginning treatments for one-third of the test. The purpose of this was to distribute the effects of any bad roving spindles among all three ginning treatments, and thus to cancel spindle effects. Spinning was performed on 9 spinning frame sides using a total of 1,188 spindles. The cottons were distributed randomly over each frame in groups of 11 spindles each. Spinning end-breakage rates were determined over a total of 61,776 spindle hours.

TABLE I. PROCESSING CHARACTERISTICS

	Ginwet	Ginmild	Ginhot
Clemson Data			
Waste, picker and card (%)	6.20	6.44	6.98
Neps in card web (per 100 sq. in.)	8	10	8
Spinning end breakage	Low	Low	Low
Joanna Data			
Waste			
Opener (%)	0.22	0.26	0.22
Picker (%)	1.71	1.50	1.56
Card (%)	3.80	3.70	3.96
Carding back and front white waste (%)	1.86	2.53	1.91
Total (%)	7.59	7.99	7.65
Nep/grain—carded sliver	16.8	18.9	16.1
Spinning ends down/1000 spindle hrs.*	26.22	29.87	31.81
Shirley Analyzer, nonlint content of waste (%)			
Opener motes (200-g. sample)	80.7	82.6	82.0
Opened raw stock (100 g.)	2.6	3.1	3.2
Picker motes (200 g.)	80.1	82.3	80.9
Picker lap (100 g.)	0.8	2.0	1.1
Card flat strips (200 g.)	17.2	14.1	16.5
Card motes and fly (200 g.)	33.0	34.4	42.7

* Detailed data in *Appendix C.*

The primary difference observed between the cottons was in their spinnability (Table I). Spinning ends-down rates increased with higher drying temperatures, being 11.1% and 21.4% higher for the Ginmild and Ginhot samples, respectively. (Analysis of the data appears in *Appendix C.*)

There were no differences between any of the cottons with regard to opener-, picker-, or card-waste percentages. However, waste compositions as determined with a Shirley Analyzer showed somewhat greater nonlint content for the heated cottons. This effect was in the opposite direction from that expected and is shown in Table I. All the cottons gave essentially the same nep count on samples of card sliver blended and prepared at TRI [12]. The results appear in Table I.

Properties of Yarns and Fabrics

Carded 36/1 and 50/1 Yarns Spun at the Clemson Cotton Laboratory

Yarns from the preliminary spinning trial were tested at Clemson for skein strength and appearance, and at TRI for single-end breaking load and elongation and for evenness on a Fielden evenness tester. Skein strength and yarn appearance decreased slightly with heating (Table II). All three cottons showed significant differences in the breaking load of 36/1 yarns, with a decrease of 7.2% from Ginwet to Ginhot. For the 50/1 yarns, Ginmild and Ginhot gave the same breaking load, but both were about 6% lower than Ginwet. There was a significant decrease with heating in the evenness of both 36/1 and 50/1 yarns.

Carded 41/1 Filling Yarn Spun at Joanna Cotton Mills Company

Yarn tests at Joanna showed no differences among the cottons in yarn size and percentage nonuniformity as measured by a Brush Uniformity Analyzer. However, both heated cottons gave a greater percentage variation in count and lower skein breaking strengths and break factors than the Ginwet control (Table II). As has been described in previous work [10] the yarn-appearance grade was lowered slightly with the higher temperature drying, from B− to C+. All these differences, although they may not be of practical importance, are real differences within the precision of the measurements.

TABLE II. PROPERTIES OF YARNS AND FABRICS

	Ginwet	Ginmild	Ginhot
36/1 *and* 50/1 *made at Clemson*			
Yarn strength and appearance, 36/1 (lbs. grade)	73.8 B	71.0 C+	70.3 C+
Yarn strength and appearance, 50/1 (lbs. grade)	45.8 C+	45.1 C+	44.2 C+
Average yarn strength index	109.6	111.2	109.6
Average yarn appearance index	105	100	100
36/1 single-end breaking load (g.)	263	254	244
single-end elongation (%)	6.8	6.9	6.8
% mean deviation (Fielden)	8.61	8.91	8.98
50/1 single-end breaking load (g.)	168	158	160
single-end elongation (%)	6.2	6.2	6.3
% mean deviation (Fielden)	9.88	10.41	10.82
41/1 *made at Joanna*			
Yarn			
Count	39.13	39.42	39.12
% variation (count)	7.8	12.4	11.2
Skein break (lbs.)	57.3	52.5	54.4
Break factor	2242	2066	2125
% nonuniformity (10 in. Brush)	112	114	115
Yarn appearance grade	B−	B−	C+
Single-end breaking load (g.)	211	207	193
Single-end elongation (%)	7.0	7.1	6.9
% mean deviation (Fielden)	4.31	4.46	4.58
Cloth strength (test cottons in filling)			
Grab method (lbs.)	62	58	60
Ravel method (lbs.)	57	54	56
Elmendorf (g.)	960	930	938

TABLE III. CLASSER'S EVALUATION

	Greenwood Cooperative	U.S.D.A.—Clemson Laboratory*	Joanna Cotton Mills	Dan River Mills	Deering Milliken Service Corp.
Grade					
Ginwet	M	SLM+	M	M− (leaf)	M
Ginmild	M	M	M	M	M+
Ginhot	M	M	M	M	M
Staple					
Ginwet	1 3/32	1 1/16	1 1/16	1 1/16	1 1/16
Ginmild	1 3/32	1 1/32	1 1/32	1 1/16	1 1/16
Ginhot	1 3/32	1 1/32	1 1/16	1 1/16	1 1/16
Character					
Ginwet	—	—	—	Good	Fair–Good
Ginmild	—	—	—	Good	Fair–Good
Ginhot	—	—	—	Good	Fair

* Based on sample ginned on laboratory 20-saw gin, rather than on classer's samples from commercially ginned bales.

Tests on yarn samples at TRI (Table II) showed a significant decrease with heating in single-end breaking load and in evenness as tested on a Fielden instrument. In evenness not only are both heated cottons different from Ginwet but also Ginhot gives significantly poorer values than Ginmild. In yarn strength the only statistically significant difference is that between Ginhot and the other two cottons, amounting to about 8%.

The 41/1 yarns were used as filling in weaving samples of 40-in., 80 × 92 cloth for testing at the Joanna laboratory. The warp used was not of the test cottons. The cloth strength was measured in the filling direction using the Grab, Ravel, and Elmendorf tests. The results indicate a slightly, but consistently, lower strength for the Ginmild and Ginhot fabrics than for the Ginwet (Table II).

Fiber Properties

Classer's samples of the test cottons were classed by various independent organizations. No distinction could be made between any of the cottons, although there was some indication of the increase in grade and decrease in staple length found in other similar trials [15]. In this case, grade improvement was minimized due to the fact that the cottons were hand picked and there was no cleaning performed on them. (See Table III.)

The fiber length was tested with a Fibrograph at Joanna and at Clemson. As illustrated in Table IV, the results indicate a lower length of the Ginmild and Ginhot.

Fiber fineness was measured with the Micronaire at Deering Milliken Service Corporation, Joanna, and TRI. At TRI the same samples were also tested for maturity by examining random selections of fibers under the microscope after treatment with

TABLE IV. CONVENTIONAL FIBER PROPERTIES

Property			Ginwet	Ginmild	Ginhot
Fibrograph upper-half mean length (in.)—Joanna			1.13	1.10	1.11
Fibrograph upper-half mean length (in.)—Clemson			1.11	1.11	1.10
Fibrograph mean length (in.)—Joanna			0.96	0.90	0.92
Fibrograph mean length (in.)—Clemson			0.95	0.94	0.90
Fibrograph uniformity ratio—Joanna			85	82	83
Fibrograph uniformity ratio—Clemson			86	85	82
Micronaire fineness (μg/in.)—Joanna			4.50	4.50	4.50
Micronaire fineness (μg/in.)—Deering Milliken			4.70	4.55	4.60
Micronaire fineness (μg/in.)—TRI			4.62	4.69	4.67
Percent maturity—TRI			81.1	78.6	82.3
Pressley strength tester (index)—Joanna			6.8	6.9	6.8
Pressley strength tester (1000 p.s.i.)—Joanna			74	74	74
Tensile strength—Deering Milliken			81.6	80.7	78.9
Pressley strength on Instron (index)—TRI			7.2	6.9	7.0
Pressley strength on Instron (1000 p.s.i.)—TRI			78	74	76
Grams per grex bale	jaw spacing	0 mm.	3.85	3.70	3.70
		1.5 mm.	2.50	2.45	2.45
		5 mm.	1.85	1.75	1.75
roving	jaw spacing	0 mm.	3.90	3.80	4.00
		1.5 mm.	2.50	2.55	2.50
		5 mm.	1.90	1.90	1.80

an 18% solution of NaOH. All the cottons gave the same values (Table IV).

Fiber-bundle strengths were measured at Joanna and at Deering Milliken on the Pressley strength tester in the conventional manner. At TRI bundle-strength tests on bale and roving samples were performed on the Instron tensile tester, using Pressley clamps with spacings of 0, 1.5, and 5 mm. These latter results are reported in Table IV in units of grams per grex, while the results of the bale tests at a clamp spacing of 0 mm. also appear in conventional Pressley units. Despite a trend toward lower bundle strength with increasing heat in drying, none of the cottons showed any differences in the above parameters.

Samples of the bale cotton were blended [4] for uniformity and were sent to the U. S. Department of Agriculture in Washington for test on the Nickerson-Hunter cotton colorimeter [11]. The results as shown in Table V are essentially the same for all cottons.

Deering Milliken tested the cottons for fluorescence. Numerical values assigned indicate that the Ginhot fluoresced slightly more than the Ginwet, whereas the Ginmild fluoresced less than both the other cottons. The values appear in Table V.

At TRI the cottons were examined under ultraviolet light by the method of Sheehan, Bailey, and Compton [13], using a Hanovia lamp No. 16106 giving off ultraviolet light principally of 3660 Å. The three cottons were compared with one another and with standard samples which had been heated in an oven to produce ivory fluorescence. No color differences could be detected among the ginned cottons. The fluorescence of the test cottons was not comparable to that of the oven-dried samples.

Bale samples of the cottons were tested for their alkali-centrifuge values [8]. The results (Table V) showed a significant increase in the take-up of caustic by both heated cottons. Since the cottons are of the same maturity or cell-wall thickness, the conclusion is that drying to a low moisture content, either quickly at high temperatures or slowly at moderate temperatures, is sufficient to damage the fiber.

The intrinsic viscosities of Ginwet and Ginhot in cupriethylenediamine solution were determined and found to be 24 and 25 units, respectively. This difference is not significant in the test used, so that the degree of polymerization may be considered to be the same for both cottons.

Moisture-content readings were taken with the Hart Moisture Meter at the gin and during processing at Joanna. Raw-cotton samples transported in sealed containers were tested for moisture content by oven drying. In ginning, the Ginmild and Ginhot were both dried to a moisture content of about 3.8%, while Ginwet gave a value of 5.9%. The cottons quickly leveled off to the same value in the card room and remained at a common moisture level throughout the entire processing trial (Table VI).

Tests at TRI for equilibrium moisture contents indicated a drop in moisture content with increasing ginning heat for both absorption and desorption (Table VI). This observation may be interpreted as indicating an increase in crystallinity or a reduction in "accessibility" with heat [6].

The above evidence for a difference in structure also suggested a possible difference in the dyeing characteristics of the cottons. Bale samples of each of the cottons were therefore dyed according to the method of Goldthwait, Smith, and Barnett [5]. It was found that the Ginwet dyed a distinctly greener shade than either of the heated cottons. Although the test used here is primarily a test for cotton-fiber maturity, it has been shown that the color obtained is also a function of fiber structure [16]. Since the samples employed here were all of the same maturity, the difference in color may be interpreted as being due to a difference in fiber structure, confirming the observations on equilibrium moisture content.

Single fibers from samples of each ginning treatment and from cotton bale, picker lap, and roving were tested for their mechanical properties. Two

TABLE V. SPECIAL FIBER PROPERTIES

	Ginwet	Ginmild	Ginhot
Nickerson-Hunter cotton colorimeter — Reflectance *Rd*	76	75.3	75.8
Nickerson-Hunter cotton colorimeter — Yellowness $+b$	8.7	8.6	8.7
Fluorescence*—Deering Milliken	3	5.5	2
Alkali-centrifuge value—TRI	188.1	194.0	194.7
Intrinsic viscosity in cupriethylenediamine solution	24	—	25

* Fluorescence ranked in order of descending magnitude.

operators, working in parallel, each selected 24 fibers at random from samples of each ginning condition and each processing station, for a total of 432 fibers. The following properties were measured: area of fiber cross section, breaking load, elongation to break, Hookean slope, uncrimping energy, elastic modulus, and breaking stress. Testing was done on the Instron tensile tester equipped with vibroscope and integrator, employing procedures previously described [9]. Results appear in Table VII. There were no significant differences between the ginned cottons in any of the parameters measured. The effect of processing from bale to roving was to decrease elongation to break, and to decrease by 45% the energy required to uncrimp the fibers.

Card slivers, finisher drawing slivers, and rovings were tested at Joanna for assembly size and for percentage nonuniformity on a Brush Uniformity Analyzer. Again there were no differences between the cottons.

Roving samples were tested at TRI for strength and stiffness as given by the steepest slope of the force-extension curve [3]. Ginmild and Ginhot were 12% and 34% weaker, respectively, than Ginwet, with a corresponding decrease in roving stiffness of 8% and 13% (Table VIII).

Samples of bale and roving were tested for number-length distribution at TRI on a modification of the Wool Industries Research Association Fiber Length Tester [1]. The machine measures fibers as

TABLE VI. MOISTURE CONTENTS

	Hart Moisture Meter			Oven Dry		
Station	Ginwet	Ginmild	Ginhot	Ginwet	Ginmild	Ginhot
Seed cotton at gin stand	6.7	4.5	4.9	—	—	—
Lint at bale slide at Stoneville	5.9	3.8	3.8	—	—	—
Lint at bale slide on samples at TRI	5.4	2.9	3.0	5.91	3.82	3.65
At Joanna warehouse	—	—	—	5.71	5.15	5.54
Opened to condition in Joanna warehouse	—	—	—	5.98	5.96	5.63
Bale at opening	5.4	4.4	4.3	—	—	—
Picker lap	5.5	5.7	5.8	—	—	—
Carded sliver	4.9	4.8	4.6	—	—	—
Drawing sliver	4.8	4.7	4.6	—	—	—
Roving	5.4	5.2	5.2	—	—	—
Roving in spinning frames	5.5	5.7	5.6	—	—	—
Equilibrium moisture contents						
Absorption	—	—	—	7.43	7.26	7.19
Desorption	—	—	—	8.20	8.03	7.89

TABLE VII. SINGLE-FIBER PROPERTIES

Property	Units	Station	Ginwet	Ginmild	Ginhot
Cross-sectional area	$cm.^2 \times 10^6$	All*	1.25	1.25	1.26
Breaking load	g.	All*	4.43	4.83	4.67
Elongation to break	%	All*	8.49	9.54	8.85
Hookean slope	g./%	Bale	0.515	0.445	0.521
		Picker lap	0.540	0.534	0.522
		Roving	0.646	0.599	0.612
Energy to uncrimp	$(g./cm.^2) \times 10^3$	Bale	1.72	1.86	1.98
		Picker lap	1.96	1.79	1.91
		Roving	1.02	0.95	1.06
Elastic modulus	$(g.\ cm.^{-2}$ for 1% ext.) $\times 10^{-6}$	Bale	0.436	0.363	0.422
		Picker lap	0.420	0.427	0.397
		Roving	0.526	0.500	0.619
Breaking stress	$(g./cm.^2) \times 10^{-6}$	All*	3.63	3.94	3.80

* Data for fibers at all three stations were averaged when statistical analysis showed no significant station effects. A total of 48 fibers was tested for each cotton at each station: bale, picker lap, and roving. A total of 432 fibers was tested.

short as 0.2 in. and transmits the length measurement to an IBM Reproducing Punch for automatic introduction to an IBM punched card. Fibers shorter than 0.1 in. are registered manually. The fibers are grouped into 0.1-in. length increments.

The results of measurement of the length of 1000 fibers of each cotton from both bale and roving samples are illustrated in Figures 1 and 2 and presented in condensed form in Table IX. It can be seen that Ginhot consists of more short fibers and fewer long fibers than Ginwet in both bale and roving. The length distribution of the Ginmild cotton in the bale is only slightly shorter than that of the Ginwet. Processing into roving, however, changes the number-length distribution of the Ginmild to the extent that it compares more closely to that of Ginhot.

Discussion and Conclusions

On the samples described the main differences in processing were in the spinning end-breakage rates, which were found to be greater for the cottons that had been overdried before ginning than for the control sample. The property which it is felt contributes most to this difference is the number-length distribution. It would appear logical that the larger number of short fibers in the rovings of the heated cottons than in the roving of the Ginwet interferes to some extent with the drafting process. Thus the yarns and the rovings of the overdried cottons are somewhat more uneven and weaker than those of the Ginwet control. These factors result in the significant increase in spinning ends down observed.

It should be noted that, although the over-all spinning end-breakage rate observed is acceptable in average mill operation, an increase of 21.4% in the rate would be felt rather strongly in an efficient mill operation. Furthermore, it is altogether likely that this rate would have been increased still further had the heated cottons been passed through cleaning equipment at the gin and thereby suffered even more damage.

Comparison of the number-length plots in Figures 1 and 2 indicates that during processing more fiber tips are broken off fibers of the Ginhot and Ginmild than off fibers of the Ginwet sample. The Shirley Analyzer results on samples of waste and stock are of particular interest in this connection (Table I). It was found that when the lint was removed from the samples the remaining "nonlint content" of the heated and overdried cottons was consistently greater than that of the control. It would be expected that the nonlint content of the overdried cotton would be less rather than greater than that of the control. One explanation for this discrepancy might be that in passing through the Shirley Analyzer the broken fiber tips and other very short fibers are not separated with the lint fraction but become part of the nonlint fraction going into the dust bag. This effect is quite apparent in the values for card motes and fly.

It was hoped that some rapid and simple method might be found to identify the overdried cottons while they were still in the bale, but the only tests which showed any differences between the cottons are relatively slow and difficult to perform. These tests measured equilibrium moisture contents, alkali-centrifuge values, and the number-length distribution. Of these, measurement of number-length distribu-

TABLE VIII. SLIVER AND ROVING PROPERTIES

Property	Ginwet	Ginmild	Ginhot
Carded sliver (grains/yd.)	46.6	48.1	46.6
% nonuniformity (1-yd. brush)	20.0	21.1	21.0
Drawing sliver (grains/yd.)	56.9	56.9	57.4
% nonuniformity (1-yd. brush)	24.0	19.0	23.1
Roving—hank size	2.09	2.15	2.11
% nonuniformity (1-ft. brush)	30.3	31.6	30.3
Strength (g.)	250.0	219.4	165.9
Slope (g./%)	120.7	111.6	105.0

TABLE IX. FIBER NUMBER-LENGTH DISTRIBUTION*

Length groups (in.)	Bale			Roving		
	Ginwet (%)	Ginmild (%)	Ginhot (%)	Ginwet (%)	Ginmild (%)	Ginhot (%)
0.1–0.4	28.6	28.0	34.4	27.5	32.3	35.3
0.5–0.8	23.4	26.0	26.4	28.5	29.4	29.6
0.9–1.2	42.9	40.8	35.6	41.3	36.6	34.7
1.3–1.5	5.1	5.2	3.6	2.7	1.6	0.5

* Plots of number-length data in 0.1-in. length increments appear in Figures 1 and 2.

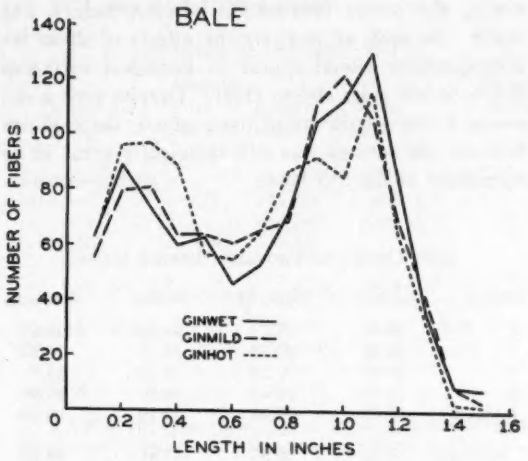

FIG. 1. *Number-length plot of bale samples of the gin-dried cottons. The mean values are: Ginwet—0.741 in; Ginmild—0.732 in; Ginhot—0.685 in.*

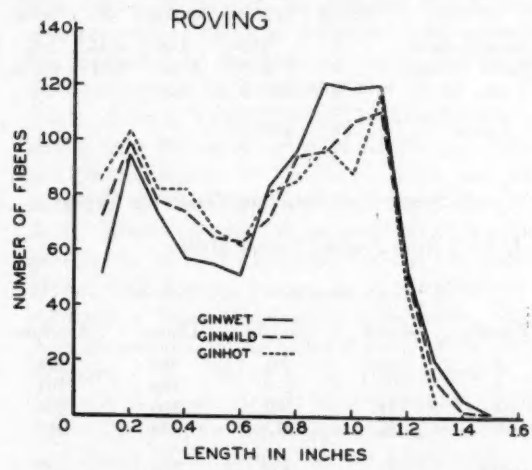

FIG. 2. *Number-length plot of roving samples of the gin-dried cottons. The mean values are: Ginwet—0.721 in; Ginmild—0.676 in; Ginhot—0.646 in.*

tion is probably most desirable because it appears to be the specific cause of the processing differences observed. In this respect the results of the "overdrying" study are similar to those obtained with "cavitomic" cotton previously reported [17]. In that instance a length distribution biased in the direction of short fibers was also found and indicated as the cause of inefficient spinning and poor yarn quality. Both of these investigations emphasize the need for a rapid and sensitive method of evaluating fiber-length distribution in raw cotton.

Appendix A

Ginning Data

The data were collected and provided by the Stoneville Ginning Laboratory under the supervision of Mr. Charles M. Merkel, Agricultural Engineer.

Drier Specifications

Air Flow: 6000 cu. ft./min.
No. 1: 17 shelves, 4 ft. wide, 15-in. spacing.
No. 2: 18 shelves, 4 ft. wide, $10\frac{3}{8}$-in. spacing.

Drier Temperatures (°F)

		No. 1 In	No. 1 Out	No. 2 In	No. 2 Out
Ginwet	Both bales	No heat		No heat	
Ginhot (high heat, 1 drier)	Bale *A*	450	187	No heat	
	Bale *B*	460	242	No heat	
Ginmild (low heat, 2 driers)	Bale *A*	240	170	200	170
	Bale *B*	290	182	220	180

Production Data

		Gin time (min.)	Lint bale weight (lbs.)	Seed weight (lbs.)
Ginwet	Bale *A*	15.05	496	830
	Bale *B*	14.15	489	810
Ginmild	Bale *A*	16.16	446	810
	Bale *B*	18.55	540	945
Ginhot	Bale *A*	Not taken	465	735
	Bale *B*	18.30	507	868

Appendix B

Processing Organization and Procedures

All processing was done in the production areas of Joanna Cotton Mills under the full-time supervision of laboratory personnel. The cottons were handled as 6 separate 1-bale lots and processed in series in a random order through drawing. In roving and spinning the cottons were processed together in parallel. Moisture-content readings were taken at all stations with the Hart Moisture Meter.

Opening and picking were performed on a line consisting of two F-7 openers, one 1953 Centennial

opener, and one Southeastern modification of a Saco-Lowell two-beater, single-process picker. Laps of 14.5 oz./yd. were produced. The entire line was cleaned after each lot, and the wastes were weighed and sampled for later analysis.

Seven Saco-Lowell revolving flat cards equipped with continuous strippers were used to produce 46 grain/yd. card sliver. After each cotton was carded, wastes were collected and samples of waste and sliver were taken for testing.

One Saco-Lowell lap winder was used to produce 16-end laps weighing 736 grains/yd., which were then drawn into 57 grains/yd. draw sliver on four Saco-Lowell controlled-draft drawing frames with four deliveries and 5-over-5 rolls.

Roving of 2.10 hank count was produced on one Saco-Lowell J-3 10 × 5 roving frame divided into 6 groups of spindles. Each group was assigned 1 bale. Twice during the roving operation the cottons were rearranged in such fashion that each spindle group carried a cotton from each of the main ginning treatments for one-third of the test. Samples were taken during each time period.

Single-creel spinning into 41/1 filling yarn was done on 4½ Whitin frames equipped with Saco-Lowell Roth drafting system. Each of the 9 frame sides was divided into 12 groups of 11 spindles each, and a cotton was randomly assigned to each group. Each frame carried 4 groups of each of the 6 cotton bales. Ends-down data accumulated for 52 consecutive hours by laboratory personnel. A sample bobbin of yarn was taken from each of the 108 groups once during spinning for testing.

Appendix C

Analyses of Variance

1. Spinning Ends Down

Ends down were counted during the spinning for a total of 61,776 spindle hours. Following are the table of mean values and the results of an analysis of variance on the data.

NOTE: The analysis of variance shown below does not include factors of conditioning, shifts, and first-order interactions which in a preliminary analysis were found to be negligible. The half-frame was omitted from this analysis because the cottons were homogeneously distributed among frames rather than among frame sides. Thus a rigorous analysis by frame sides was not possible. A trial analysis ignoring the cotton distribution inhomogeneities was made. In such an analysis the effects of these inhomogeneities would appear as increased variances due to frame sides and to error. Despite such a decrease in the sensitivity of the analysis, the variance between the cottons was still sufficiently great to be significant at the 5% level.

ENDS DOWN PER THOUSAND SPINDLE HOURS

Frames	Ginwet	Ginmild	Ginhot	Averages
3	20.98	27.32	34.53	27.61
4	24.48	27.53	28.19	26.73
5	20.32	22.29	34.53	25.71
6	33.00	38.02	30.59	33.87
7 (½) Fr.	38.46	38.46	30.59	35.84
Averages	26.22	29.87	31.81	29.30

ANALYSIS OF VARIANCE OF SPINNING ENDS DOWN

Source of variance	Degrees of freedom	Sums of squares	Mean squares	*F*	Significance level
Between cottons	2	38.9	18.45	4.39	2%
Between frames	3	64.4	21.47	5.11	0.2%
Error	570	2395.0	4.20		
Totals	575	2498.3			

2. Single-End Breaking Loads for Yarns

A. 41/1 *from Joanna Cotton Mills*

MEAN BREAKING LOAD (GRAMS)

Frames	Ginwet*	Ginmild	Ginhot	Averages
3	198	204	190	197
4	200	210	193	201
5	221	202	196	206
6	225	213	195	211
Totals	211	207	193	

* Each cotton-by-frame mean is based on 40 breaks.

ANALYSIS OF VARIANCE

Source of variance	Degrees of freedom	Sums of squares	Mean square	*F*	Significance level (%)
Between cottons	2	27,673	13,837	6.2	5
Between frames	3	33,628	11,209	5.0	5
Cottons-frames interaction	6	13,364	2,227	2.0	6
Error	468	515,766	1,102		
Totals	479	590,431			

B. 36/1 and 50/1 from Clemson

ANALYSIS OF VARIANCE–36/1*

Source of variance	Degrees of freedom	Sums of squares	Mean square	*F*	Significance level (%)
Between cottons	2	10,103	5,052	7.56	<0.1
Error	177	118,284	668		
Totals	179	128,387			

ANALYSIS OF VARIANCE–50/1*

Between cottons	2	3,693	1,846	4.79	1
Error	177	68,083	385		
Totals	179	71,776			

* Each of the above analyses of variance is based upon a total of 180 breaks. The mean values appear in Table II.

Acknowledgment

A study of the type herein described would have been impossible without the generous and enthusiastic cooperation of many individuals and agencies. The authors are, therefore, especially indebted to Burt Johnson of the Production and Marketing Division, National Cotton Council of America, for assisting with the organization of sample preparation and ginning phases; to Charles R. Sayre and staff members of the Delta and Pine Land Company, Scott, Mississippi, for the preparation of a homogeneous lot of seed cotton for the test; to Charles Merkel and Vernon Moore, U. S. Department of Agriculture Stoneville Ginning Laboratory, Stoneville, Mississippi, for the ginning test; and to Walter Regnery, J. L. Delany, J. K. Waites, and F. H. Simpson of Joanna Cotton Mills Company, Joanna, South Carolina, for the very considerable assistance and special efforts required to run a processing trial in a production mill.

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Preparation and Properties of a Wool Protein Free of Disulfide Cross-Links

I. J. O'Donnell

Biochemistry Unit, Wool Textile Research Laboratory, Commonwealth Scientific and Industrial Research Organization, Melbourne, Australia

Abstract

Modified wools have been prepared in which all the disulfide bonds have been severed by reduction and alkylation under conditions not conducive to peptide-bond rupture. The possibility of introducing strongly lyophilic groups into the wool proteins by this method was investigated. The solubility and other properties of —S carboxamidomethyl wool and extracts from it were studied.

BEFORE wool can be characterized by the usual physicochemical methods of diffusion, electrophoresis, ultracentrifugation, etc., it must be solubilized. More than this, if such physical measurements are to yield a maximum of knowledge regarding the intact wool fiber, the bonds broken or other changes incurred during the process of solubilization should be known.

Of the various bonds concerned in the insolubility of wool, it has long been realized that the disulfide cross-links of cystine are of vital importance. An analogy may be drawn with other macromolecules, such as synthetic polymers, where two- or three-dimensional networks formed by cross-linking lead to gel formation or insolubility. Whether these cystine bonds are uniquely responsible for the insolubility of the wool proteins could be investigated by breaking all the disulfide bonds in wool without affecting the other bonds. This may be effected by either complete oxidation or complete reduction of the disulfide bonds.

Of the various methods for the oxidative rupture of the disulfide bonds of wool, that using dilute aqueous peracetic acid, as used by Alexander, Hudson, and Fox [3], is the only one which, it is claimed, causes no significant peptide-bond hydrolysis. Some 90% of the oxidized product is soluble in dilute ammonia [2] because of the presence of charged lyophilic sulfonic acid groups in place of the disulfide cross-linkages in the original wool molecules.

If, indeed, this peracetic acid and subsequent dilute ammonia treatment does not rupture peptide bonds, the breaking of all disulfide links by reduction together with the introduction of charged lyophilic groups into the fiber might be expected to produce a similar protein solution. Reduction methods suffer from the disadvantage that some of the thiol groups so produced are susceptible to reoxidation in the air to the disulfide form; hence, the state where all the cystine bonds of wool are reduced is not a stable one.

It has already been shown [13] that thioglycollic acid is capable of reducing at acid pH values roughly one-half of the cystine of wool, and the extent of reduction increases with increasing pH. It has also been found [8] that successive reductions at acid pH values followed by alkylation of the resulting thiol groups at a slightly alkaline pH value effects the conversion of some five-sixths of the cystine sulfur to S—alkyl groups. In the present work, wool has been repeatedly reduced with thioglycollic acid at a slightly acid pH value, with subsequent alkylation of the thiol groups so formed. The possibility of introducing strongly lyophilic groups into the wool proteins by the use of a suitable alkylating agent has been studied, and the effect of buffers at various pH values on the residual cystine content of the wool has been investigated.

Experimental

Most of the work was carried out with air-dried merino 64's root wool containing 11% moisture. Air-dried Corriedale 56's wool was used for certain experiments. The wool was cleaned by successive extractions with hot ethanol after which it was washed with distilled water.

The total cystine-cysteine content of wool hydrolyzates was determined by the method of Shinohara

[15]. Hydrolysis was carried out by refluxing 0.500-g. samples of wool with 20 ml. of 5*N* HCl for 6 hrs. Amide nitrogen determinations were carried out on these hydrolyzates by steam distillation of ammonia from solutions adjusted to pH 9.5.

Disulfide bonds in wool were reduced by immersing 0.500 g. of wool in 0.4*M* sodium thioglycollate solution at pH 5.6 for 16 hrs. The wool was then thoroughly washed in water and ethanol. The thiol groups formed in this way could be alkylated by treating 0.500 g. of the reduced wool for 16 hrs. with 20 ml. of 0.05*M* buffer containing 0.2 g. of iodoacetamide, 0.2 ml. of methyl iodide, or 0.1 g. of iodoacetic acid. A similar reaction was attempted with 0.3 g. of iodomethane sulfonic acid, 0.5 g. of β-chlorethyldiethylamine, and 0.1 g. of iodocholine iodide.

Methylation of wool was carried out by allowing the wool to stand with 0.1*N* anhydrous hydrogen chloride in methanol at 65°C for 4 hrs. (Alexander *et al.* [1]).

The amount of wool passing into solution was determined by direct weighing of the dried protein from an aliquot of solution or by Kjeldahl nitrogen determination. The solubility of treated wools was determined by allowing 0.500 g. of wool to stand in 25 ml. of the appropriate aqueous solution either at room temperature or at 65°C and determining the protein content of the supernatant liquor after a suitable time interval. When 8*M* urea or 10% dodecyl sulfate was used as a solvent, the modified wool fibers swelled greatly and could be disintegrated in a Waring Blendor. Such swollen fibers were beaten in the Blendor and allowed to stand for a further period prior to determining the protein in solution. In a few instances the solubility was determined by shaking the wool with solvent and glass beads in a Erlenmeyer flask for 7 hrs. to eliminate diffusion difficulties.

The fraction extracted with urea was dialyzed to remove urea and freeze dried. The reaction of this material with detergent was followed by titrating 2% (w/v) solutions of this protein in buffers at various pH values with a solution of sodium dodecyl sulfate containing 23 mg. of detergent per 100 ml. of solution. The sodium dodecyl sulfate used for this purpose was prepared from Eastman Kodak lauryl alcohol by the method of Draeger *et al.* [5], and could be removed entirely from a solution by dialysis against running tap water, using Visking cellulose tubing. Commercial detergents could not be removed completely by dialysis because of the presence of higher homologs.

A conventional Tiselius moving-boundary apparatus was used for electrophoretic experiments with soluble wool fractions.

Results

1. *Effect of Buffer on the Cystine and Cysteine Contents* of Normal and Partially Reduced Wool*

It may be observed from Table I that no significant amount of cystine was removed from normal wool by extraction with buffer at pH 7.2–8.6, and very little was removed at pH 9.2. With reduced wool the effect of buffer was to decrease the cystine and cysteine content to a small extent. Alkylation of the thiol groups of reduced and normal wools was therefore carried out at pH 7–7.2.

2. *Effect of Iodoacetamide at pH 7.2 on the Cystine and Amide Content of Normal Wool*

It may be seen from Table II that iodoacetamide had little effect on the cystine content of normal wool, but there was an appreciable increase in the amide nitrogen content of the wool, indicating that the iodoacetamide reacted with certain groups. These are probably the amino groups in the wool

TABLE I. CYSTINE CONTENT OF WOOL AFTER BUFFER TREATMENTS*

pH of buffer	State of wool	Time of treatment with buffer (hrs.)	—S—S— + —SH as % S in wool
	normal	nil	2.65
7.2	normal	24	2.71
	normal	48	2.67
8.0	normal	24	2.66
	normal	48	2.67
8.6	normal	24	2.71
	normal	48	2.64
9.2	normal	24	2.57
	normal	48	2.58
	reduced once		2.65†
5.2	reduced once	144	2.52
8.0	reduced once	144	2.40
8.6	reduced once	144	2.46
9.2	reduced once	144	2.41

* 0.500 g. of wool standing in 0.05*M* buffer.
† —S—S— = 1.42; —SH = 1.23.

* Untreated wool was found to contain practically no free thiol groups (approximately 0.01 as percent S).

[9, 12], since normal wool contains practically no free thiol groups.

3. *Reduction of Wool and Alkylation of the Thiol Groups Produced*

It was found that sodium iodomethane sulfonate (at pH 7.2, 8.0, and 9.2), β-chlorethyldiethylamine (at pH 8), and iodocholine iodide (at pH 4, 7, and 8) do not react with the thiol groups present in the reduced wool. However, iodoacetamide, iodoacetic acid, and methyl iodide did react in the range studied (pH 7–8). In Table III is shown the amount of disulfide remaining in wool after successive reduction with thioglycollic acid and alkylation with iodoacetamide. After 10 reductions and alkylations, practically all the disulfide had been substituted.

Table IV presents the results of alternate reduction with thioglycollic acid and alkylation with iodoacetamide under different conditions. The amide and cystine contents of the treated wools are included.

In the last column of Table IV allowance has been made for the reaction of iodoacetamide with groups other than thiol. No allowance, however, has been made for the decrease in cystine caused by the buffer in control experiments. Taking this into account, there is good agreement between the values in columns 3 and 5.

TABLE II. AMIDE CONTENT OF WOOL AFTER TREATMENT WITH IODOACETAMIDE *

Treatment	—S—S— + —SH as % S in wool	Amide N (meq./g.)
Buffer at pH 7.2	2.62	0.72
Buffer with iodoacetamide at pH 7.2	2.50	0.90

* 0.500 g. of wool standing for 24 hrs. in 20 ml. of 0.05*M* buffer containing 0.20 g. of iodoacetamide.

TABLE III. CYSTINE CONTENT OF WOOL AFTER REPEATED REDUCTION AND ALKYLATION WITH IODOACETAMIDE

No. of reductions and alkylations	—SH + —S—S— as % S in wool 56's	64's
0	2.44	2.63
1	1.16	1.15
2	—	0.49
3	0.62	0.31
4	0.18	0.26
10	0.08	0.10

4. *Solubility Properties of Wools in Which the Disulfide Bonds Have Been Completely Severed by the Formation of S—Carboxamidomethyl Groups or S—Methyl Groups*

Table V compares the solubility of the S—carboxamidomethyl and S—methyl wool with untreated material. Considerable differences in the solubility of modified wools were occasioned by the use of different dispersing agents. Shaking with glass beads was far less effective than treatment in a Waring Blendor.

The S—carboxamidomethyl wool fibers swell up very greatly in detergent or urea, and are then easily shattered by light mechanical pressure to give scale and corticular material (as seen in the phase-contrast microscope). In the absence of detergent or urea the wool loses much of the resilience of normal wool, and on treatment with 0.1*N* HCl becomes very soft even though only a small amount enters solution. It does not swell much in 0.1*N* acid or at pH 11, and

TABLE IV. CYSTINE AND AMIDE CONTENTS OF WOOL AFTER REPEATED REDUCTION WITH THIOGLYCOLLIC ACID AND ALKYLATION WITH IODOACETAMIDE

Treatment	—S—S— + —SH as % S in wool	Loss of —S—S— on treatment (as % S)	Amide nitrogen content of wool (meq./g.)	Loss of —S—S— calculated from increase in amide nitrogen (as % S)
None	2.65	—	0.75	—
Reduction and alkylation carried out 10 times (pH 6.6 buffer)	0.10	2.55	1.55	2.38
Reduction and alkylation carried out 7 times (pH 7.2 buffer)	0.30	2.35	1.50	2.29
Reduction and alkylation carried out 10 times (pH 7.2 buffer)	0.10	2.55	1.52	2.28
One reduction followed by standing for 1 mo. in pH 7.2 buffer	2.55	—	—	—

treatment in a Waring Blendor does not disintegrate the fibers.

It has been reported [6] that wool oxidized for 24 hrs. with 1.6% aqueous peracetic acid solution at room temperature and then dyed with basic dyes shows marked differentiation of the so-called H and S segments because of increased basophilia of the H segment. It is of interest to note that S—carboxamidomethyl wool oxidized in the same way with peracetic acid does not show this effect. This confirms the view [6] that the greater increase in basophilia of the H segment over that of the S segment is related to the oxidation of the disulfide bond to an acidic group. With the S—carboxamidomethyl wool, oxidation would only proceed as far as the sulfone or sulfoxide derivative. Furthermore, the S—carboxymethyl wool when stained with methylene blue at pH 7, at which pH the carboxyl groups of the modified wool would be ionized, again shows increased basophilia of the H segment, but staining with methylene blue does not occur at pH 2.6, at which pH the carboxyl groups would be un-ionized [7]. Peracetic acid-oxidized wool, on the other hand, stains at both pH values.

The soluble protein obtained by extraction of the treated wool with detergent or urea was in each case dialyzed free of solubilizing agent and freeze dried.

TABLE V. SOLUBILITY OF TREATED WOOLS IN SOLUTIONS OF BUFFER AND PROTEIN DENATURANTS

Solvent	Type of wool	Time of treatment and temperature	% Soluble
0.1*M* borate at pH 9	S—CH_2CONH_2	9 days at R.T.	2
0.1*M* borate at pH 9	normal	9 days at R.T.	nil
0.1*M* phosphate at pH 10.5–11	S—CH_2CONH_2	10 days at R.T.	8
0.1*M* phosphate at pH 10.5–11	normal	10 days at R.T.	nil
0.1*N* ammonia	S—CH_2CONH_2	5 days at R.T.	5
0.1*N* ammonia	normal	5 days at R.T.	nil
0.1*M* HCl	S—CH_2CONH_2	24 days at R.T.	6
0.1*M* HCl	normal	24 days at R.T.	nil
10% sodium dodecyl sulfate at pH 9	S—CH_2CONH_2	48 hrs. at 65°C or 16 days at R.T. (treated with Waring Blendor)	40
10% sodium dodecyl sulfate at pH 9	normal	48 hrs. at 65°C or 16 days at R.T. (treated with Waring Blendor)	nil
8*M* urea at pH 7–9	S—CH_2CONH_2	48 hrs. at 65°C or 1 week at R.T. (treated with Waring Blendor)	80
8*M* urea at pH 8–9	S—Me	96 hrs. at 40°C (treated with Waring Blendor)	80
8*M* urea at pH 8–9	normal	3 wks. at R.T.	nil
0.1*M* KOH at pH 12	S—CH_2CONH_2	20 min. at 65°C	60

5. *Properties of the Protein from S—Carboxamidomethyl Wool Obtained by Urea Extraction of the Treated Wool Followed by Dialysis to Remove Urea and by Freeze Drying*

This protein has peculiar solubility properties. It is partially soluble in water, yielding a turbid solution which can be clarified by centrifugation. As the pH is increased the solubility of the protein is increased (Table VI), but the last trace of opalescence does not disappear at pH values below 12. This opalescence reappears if the solution is dialyzed, freeze dried, and again dissolved in buffer; *i.e.*, alkali at pH 12 does not permanently remove it.

The protein dissolves completely to give a clear solution on warming slightly with 3–4*M* acetic acid. However, a trace of salt induces precipitation. Titration with detergent at pH 3.0, 4.8, 7.4, 8.0, and 9.2 showed that:

(*a*) The addition of detergent, even in excess, to the samples at pH 3.0 and 4.8 has little effect on the solubility, but for the samples at pH 7.8, 8.0, and 9.2 the addition of detergent decreases the opales-

TABLE VI. SOLUBILITY OF UREA EXTRACT OF S—CARBOXAMIDOMETHYL WOOL AFTER FREEING FROM UREA AND FREEZE DRYING

Buffer	pH	Total protein passing into solution (%)
0.05*M* 1,2-$C_6H_4(CO_2H)(CO_2K)$	4.0	10
0.052*M* KOH-0.074*M* KH_2BO_4	7.2	51
0.066*M* KOH-0.133*M* H_3PO_3	9.0	65
0.075*M* KOH-0.063*M* KH_2PO_4	11.0	90
0.1*M* KOH-0.05*M* KH_2PO_4	12.0	100

cence markedly—the higher the pH, the greater the effect.

(*b*) When approximately 2 molecules of detergent are added per free amino group of wool (assuming 0.80 meq. of free amino groups per gram of wool), the solutions at pH 7.4, 8.0, and 9.2 become quite clear. However, on cooling to 0°C, some detergent precipitates and the solutions become heavily opalescent again. Hence, it appears that some of the detergent necessary for solubilization of the protein is but very loosely bound. A similar effect was observed by other workers with other proteins [10, 14]. Electrophoresis of these solutions cannot, therefore, be carried out at the usual low temperatures.

6. Methylation of Normal and S—Carboxamidomethyl Wool

While there is very little change in the appearance or feel of normal wool on methylation, the S—carboxamidomethyl derivative of reduced wool becomes very soft and rubbery, the effect being similar to that of aqueous *N*/10 HCl on the modified wool. According to Alexander *et al.* [1], wool treated with methanolic hydrogen chloride in this manner has 70% of its carboxyl groups esterified. Hence, the majority of any salt links occurring in wool would be broken by this treatment.

7. Electrophoresis of the Urea Extract of S—Carboxamidomethyl Wool

Three preparations were investigated:

(*a*) The lyophilized extract dissolved in 0.15*M* phosphate buffer at pH 12. The protein migrated as one main peak together with a small amount of slower-moving material.

(*b*) The protein soluble in 0.1*M* veronal at pH 8.6, *i.e.*, approximately 60% of the extract. This migrated as two peaks.

(*c*) The protein insoluble at pH 8.6, *i.e.*, approximately 40% of the extract. This was dissolved in 0.15*M* phosphate buffer at pH 12, and on electrophoresis it migrated as one peak, which, however, showed considerable spread.

It could only be concluded from the electrophoretic patterns that the protein was very heterogeneous.

Discussion

There is no reason to suspect that the treatment used in the production of a disulfide-free wool, *i.e.*, reduction at slightly acid pH and alkylation at neutral or very slightly alkaline pH, has any effect on peptide bonds in the wool matrix. This is in contrast to most other methods of disulfide-bond rupture, where peptide-bond breakdown has either been proved or is suspected. Determination of end-groups by the 1,2,4-fluorodinitrobenzene method in normal and S—carboxamidomethyl wool shows no significant difference in total color yield. It should, of course, be pointed out that this does not imply that there is definitely no peptide-bond breakage in the S—carboxamidomethyl wool, since any amino groups produced in the reduction-alkylation process may have reacted with the alkylating agent, iodoacetamide.

The causes of insolubility of proteins are currently considered to be: (*a*) covalent cross-linkages giving two-dimensional networks; these could be produced by the amino acid cystine and perhaps interchain peptide linkages; (*b*) weak interactions between chains, caused by hydrogen-bonding, van der Waals' forces, or salt linkages; (*c*) unsuitable configuration and excessive chain length.

In the S—carboxamidomethyl wool the stabilizing disulfide cross-linkages have been broken, and therefore the other factors listed above must be considered to account for the solubility properties of this wool.

That salt links are not the only major cause of the insolubility of this treated wool is shown by the fact the S—carboxamidomethyl wool is not soluble in *N*/10 HCl or in buffer at pH 11. Nor is this wool, with 70% of its carboxyl groups esterified, soluble in the pH range 2–11. However, the alkylated wool becomes softer, more rubbery, and elastic on soaking in *N*/10 aqueous or methanolic acid. It is possible that this change is in some way connected with salt-link breakage.

It is true that wool contains a considerable proportion of β protein, and this might still be insoluble even though there are no intact disulfide bonds present [4]. However, it is difficult to understand why the α portion of this wool is not soluble under conditions where salt links and maybe hydrogen bonds are broken. Infrared measurements on the treated and untreated wool show that there is no great change in the α–β ratio during reduction and methylation.

The fact that these completely reduced and alkylated wools are soluble in solutions of detergent and concentrated urea is not surprising, since mixtures of urea and reducing agent or detergent and reducing agent are known to dissolve normal wool. However, the functions of the urea and detergent in these

processes are not clearly understood. Concentrated solutions of urea are reputedly very efficient agents for breaking hydrogen bonds, and this effect is no doubt partly responsible for the solubilization of the S-alkylated wools by concentrated urea. However, the fact that, after freeing the urea-extracted protein of urea by dialysis, the protein is partly soluble in water and slightly alkaline solutions whereas the S—carboxamidomethyl wool is not, leads to the suspicion that the urea may cause some peptide-bond breakdown, solubilization of some unknown "cementing substance" or histological component, or other disaggregation. The breakage of peptide bonds by urea was suggested by the work of Middlebrook [11], who carried out end-group analyses on urea-bisulfite extracts of wool, on the insoluble residue, and on untreated wool. He found that the repeat unit in the bisulfite-treated wool was half that in untreated wool. Again, it has been found [17] that solutions of egg albumin at pH 2.6 and 10.97 in 1.5–6*M* urea have their amino nitrogen contents increased considerably, thus implying peptide-bond hydrolysis under these conditions. However, Tsao [16] used 6.7*M* urea at pH 6.5 for the depolymerization of myosin, and by end-group analysis showed that there was no peptide-bond breakdown.

In the solubilization of S—carboxamidomethyl wool by detergent solutions it is envisaged that the detergent molecules introduce lyophilic groups into the protein molecules themselves. The situation is somewhat analogous to the solubilization of peracetic acid-treated wool by dilute ammonia [2] whereby the lyophilic sulfonic acid groups produced by the peracetic acid render the wool soluble in dilute alkali.

However, with S-alkylated wools in concentrated urea or detergent, as also with peracetic acid-treated wool in dilute alkali, there is an intense swelling of the fiber, and in this state the fiber is readily fractured. Hence, the insolubility of wool may be histochemical as well as chemical in character; *i.e.*, not only must disulfide bonds and perhaps salt links be broken, but also the corticular and cuticular membranes must be loosened and broken before their contents can enter solution. Even so, solution of the protein may also depend on its being in the α form and having lyophilic groups attached to it.

Maceration of normal and treated wools with glass beads in water did not increase the solubility of the wools. However, this result is not entirely surprising, as it is doubtful whether such treatment would break corticular membranes. S-alkylated wools when given similar treatment in urea or detergent became tough and rubbery, and not as much entered solution as when the wool was allowed to stand alone in the reagent or when it was treated in a Waring Blendor.

It is intended to carry out a physicochemical characterization of the proteins derived from these completely reduced and alkylated wools.

Acknowledgments

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(Manuscript received August 10, 1954.)

A New Method for Predicting Cotton Yarn Strength from the Observed Strength of a Single Count*

Philip R. Ewald† and Charles B. Landstreet†

Spinning Laboratory, Knoxville, Tennessee

Introduction

Present methods for determining the skein strength of cotton yarns at counts other than those spun include extrapolation based on two or three spun counts, and a correction recommended by the A.S.T.M. D-13 Committee in its publication, "Standards on Textile Materials." This correction, developed by M. E. Campbell [1], applicable to skein strength, is:

$$C_2S_2 = C_1S_1 - 21.7(C_2 - C_1), \qquad (1)$$

where C_1 is the observed count; C_2 is the specified count; S_1 is the observed skein strength; S_2 is the predicted skein strength; 21.7 is a constant for standard skeins.

The constant 21.7 was determined by Campbell from 400 different cottons as an average value. It is the slope of count-strength product plotted against count and actually varies from cotton to cotton.

A recent statistical study of the actual value of this constant, now designated K, was made by Webb and Richardson [4] for a number of cottons grown in two different years. Among the observations in this paper, it was noted that, if K is to be accurately determined for any one cotton, it would be necessary to spin two counts to obtain this value.

However, at the Spinning Laboratory in Knoxville, where many varieties of cottons with widely varying K are tested, the spinning of two counts per sample is usually undesirable because of the small sizes of sample available and the added time required in the spinning.

While preparing the 1952 Progress Report [3], Kerr and Den Hartog noted that the plot of skein strength *vs.* reciprocal count was linear at least over the range 22's–50's and that this linearity was true for all cottons. Accordingly, work was started by the Division of Cotton and Other Fiber Crops and Diseases to determine how far these relations extended and whether spinning a single count would suffice to predict the strength of other counts.

Procedure

A number of runs were made on different cottons to establish the nature of the curve of skein strength *vs.* reciprocal count. This relation was chosen to give a plot starting near the origin for the smallest

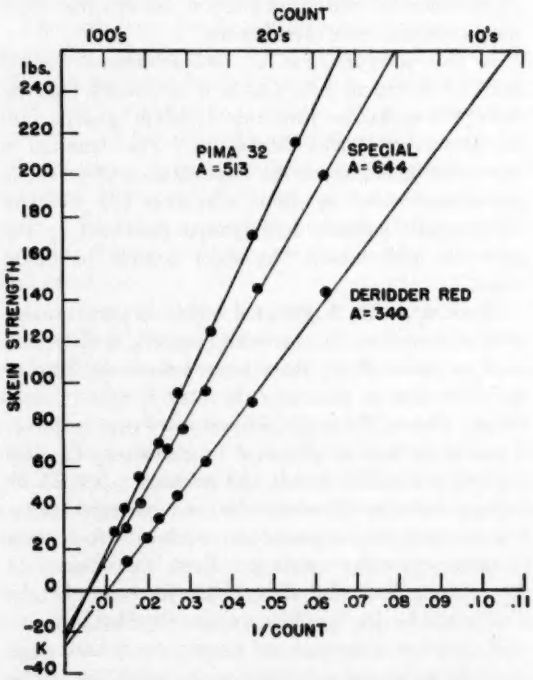

FIG. 1. *Skein strength* vs. *reciprocal count for three cottons.*

* A report on cooperative work between the University of Tennessee Agricultural Experiment Station and the U. S. Department of Agriculture.

† Field Crops Research Branch, Agricultural Research Service, U. S. Department of Agriculture.

yarns. Observations showed that the curve was essentially straight over the spinnable range, and did not pass through the origin upon extrapolation but intercepted the zero-strength axis at a definite reciprocal count, in a manner shown by three examples in Figure 1. The equation for this line is:

$$S = M(1/C) - K', \qquad (2)$$

where S = skein strength; C = count of yarn; M = slope of curve; K' = S-axis intercept value.

The strength of any count can be predicted by relation (2) if M is determined from spinning and K' can be found. Using the previous notation, the slope M is given by $(S_1 + K')/(1/C_1)$; therefore the equation becomes:

$$S_2 = (S_1 + K')(C_1/C_2) - K'. \qquad (3)$$

Rearranging:

$$C_2S_2 = C_1S_1 + C_1K' - C_2K',$$

or

$$C_2S_2 = C_1S_1 - K'(C_2 - C_1), \qquad (1)$$

which is Campbell's equation, and it is seen that the value of K' is identical with the constant K of that equation. The first few runs showed this value K to be near 21.7, as determined by Campbell.

TABLE I. VARIATION OF K WITH LENGTH AND FINENESS FOR 24 SELECTED COTTONS

Cotton number	U.H.M. (in.)	A (mm.²/mm.²)	K (by least squares)
1	0.82	638	18.11
2	0.93	390	22.12
3	0.93	340	26.63
4	0.98	371	25.44
5	1.01	553	20.01
6	1.02	394	22.98
7	1.02	479	20.39
8	1.05	434	27.00
9	1.06	420	25.97
10	1.07	644	18.53
11	1.11	447	24.31
12	1.11	469	21.77
13	1.01	407	22.82
14	1.09	920*	19.50
15	1.38	531	20.51
16	0.79	644	23.70
17	0.99	387	22.82
18	0.96	566	21.24
19	1.02	392	27.55
20	1.33	513	21.40
21	1.33	505	23.83
22	0.96	343	31.74
23	1.23	531	21.14
24	0.89	368	26.94

* Calculated from A_H.

The fact that the strength-reciprocal count curve did not pass through the origin then presented the problem of how to determine K. It was postulated that, the more the yarn resembled a homogeneous mass, the closer the strength-reciprocal count curve should approach a line going through the origin, as would be expected from strength-of-materials theory. This situation might be approached as the number of fibers per unit cross section increased, that is, with the fibers becoming increasingly fine.

Experimental Results

Table I gives data for 24 cottons selected with a wide variation in fineness, length, and breaking strength. All were spun at optimum twist multiplier as determined experimentally to give maximum skein strength. Most of them were spun into the following counts: 16's, 22's, 29's, 36's, 42's, 50's, 60's, and 70's. A few with suitable fiber properties were spun up to 90's. For each set of points, the best straight line through the set was fitted by the least-squares method to give a graph similar to Figure 1. The S-axis intercepts or K values thus determined are included in Table I.

For each cotton, a study was then made of the fiber data compared with the K value to determine whether any correlation existed. As might be expected from the postulation, a good correlation

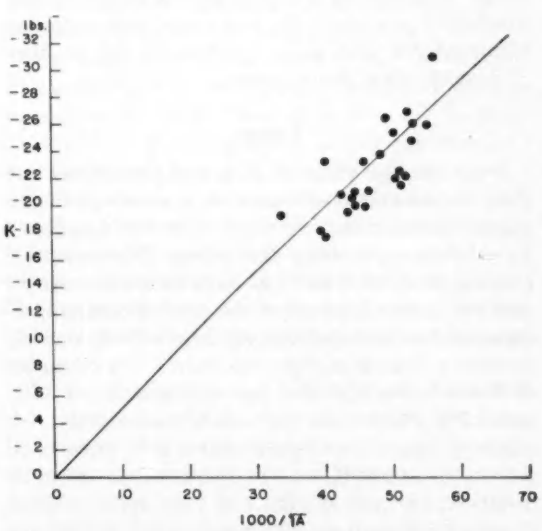

FIG. 2. *Correlation of* K *with fiber fineness.*

with the fiber fineness was obtained, in this case for K proportional to the reciprocal of the square root of fiber fineness A. A plot of this correlation is shown in Figure 2. The correlation coefficient for these data has a value of $r = 0.72$. A correlation, equally good statistically, was obtained with the first power of reciprocal A. The square-root value was chosen for reasons that will be shown later.

Using the least-squares method on the data for Figure 2 with the restriction that the correlation line pass through the origin, the relation becomes:

$$K = 500/\sqrt{A},$$

where A is mm.^{2}/mm.^{3} as measured on the arealometer [2]. The yarn skein-strength formula then resolves into:

$$S_2 = \left(S_1 + \frac{500}{\sqrt{A}}\right)\frac{C_1}{C_2} - \frac{500}{\sqrt{A}}. \qquad (4)$$

Correlations were also tried between K and fiber length, strength, and weight per unit length as calculated from fineness and immaturity, and between K and combinations of these properties. No correlations were observed except for weight per unit length, which correlated nearly as well as fineness. Weight per unit length is closely related to alrealometer fineness A, but was not used because of the computations involved.

The scatter in the data of Figure 2 is attributed partly to sampling errors, partly to errors in mechanically processing the test yarns, and partly to minor effects with weak correlations due to fiber properties other than fineness.

Errors

If an average value of K is well chosen, as was done for the Campbell equation, corrections to any spinnable count may be made from one test count for most cottons using this value. However, for cottons of unusual fineness, such as are frequently received in this laboratory, the error in assuming K constant becomes increasingly large with increasing deviation of fineness from the mean. For instance, in Table I, the high and low values of K are 27% and 22% away from the mean, respectively. A study of Figure 1 will show that a 25% error in K reflects about a 10% error in predicting the strength of 50's yarn from the data of yarn spun at 20's. Counts farthest from 20's would give the greater error of prediction and closer counts a lower error. This is the possible error due to the use of an average value for K and is in addition to processing errors and errors due to measurements of fiber properties, which are subjects not covered in this paper.

It should be noted here that in using conventional spinning techniques two counts did not suffice to establish an accurate plot of strength *vs.* reciprocal count. It was only when eight counts were spun and the least-squares relation of strength *vs.* reciprocal count was established for each cotton that the correlation between K and A became evident. Mechanical errors become dominant in processing the finer counts.

Interpretation of K

The fact that the plot of strength *vs.* reciprocal count does not go through the origin, but lies below, indicates that there are some fibers in the yarn adding to the weight to build up the count, but not cooperating to build up the strength. Figure 3 is

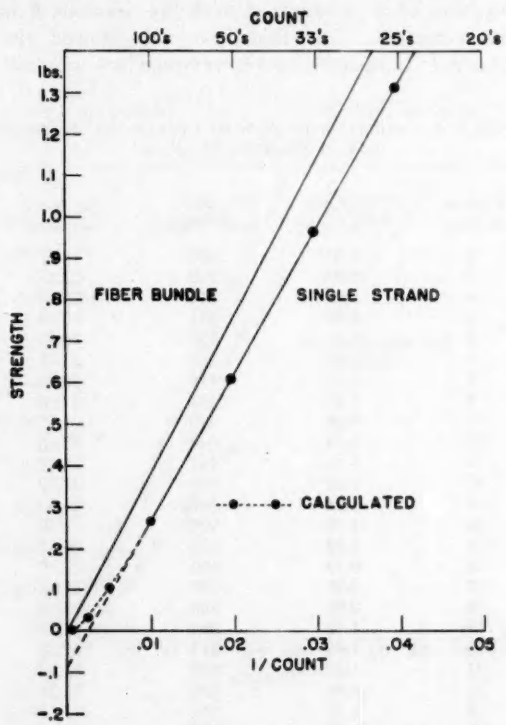

FIG. 3. *Single-strand and fiber-bundle strengths* vs. *reciprocal count for one cotton.*

an illustration of this situation. The line going through the origin is a plot of cotton fiber-bundle breaking strengths made at $\frac{1}{8}$-in. gage length on the stelometer against the weight per unit length of the bundle expressed as the equivalent reciprocal yarn count. The other solid line is a plot of single-strand breaking strength made on the IP-4 tester for yarns made to the corresponding count. Notice that the yarn does not realize the same potential as its fibers, but falls away from the origin.

A workable explanation of this behavior may be had by assuming that there is a layer of non-cooperating fibers in a yarn as cross-sectioned in Figure 4, that these fibers are on or near the surface where there is a discontinuity of yarn cross-sectional structure, and that, because this noncooperation is a surface effect, the thickness of this layer is constant for all counts for any given cotton. The equation of the yarn strength will be:

$$YS = \pi(R - \Delta R)^2 T, \qquad (5)$$

where R = yarn radius; ΔR = thickness of non-cooperating fiber layers; T = tenacity per unit cross section of cooperating fibers.

Assuming that the yarn density is constant:

$$R = K_1\sqrt{1/C},$$

where C = yarn count; K_1 = a constant.

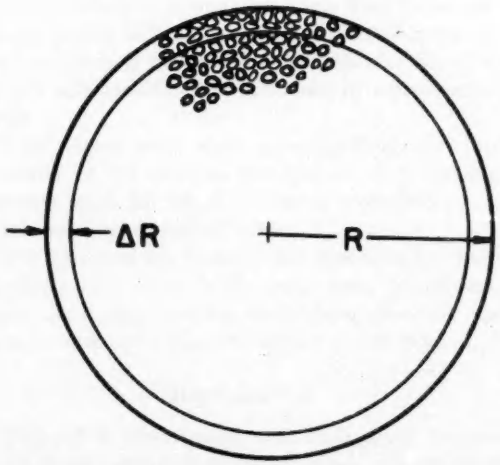

FIG. 4. *Hypothetical yarn cross section.*

The thickness of ΔR was assumed constant for any count for a given cotton, but from similar considerations it would vary for different cottons with fiber fineness. Since the fibers are irregular in shape and irregularly packed, it is easier to express the linear change of ΔR as a function of fiber cross-sectional area than of effective diameter; hence:

$$\Delta R = K_2\sqrt{p/A},$$

where p = fiber perimeter and p/A = fiber cross-sectional area [2]. Since, for most cottons, p is essentially constant,

$$\Delta R = K_3\sqrt{1/A},$$

then

$$YS = \pi T(R^2 - 2R\Delta R + \Delta R^2).$$

Dropping ΔR^2, a very small term, and substituting:

$$YS = \pi T K_1^2(1/C) - 2\pi T K_1 K_3\sqrt{1/C}\sqrt{1/A} \qquad (6)$$

or

$$YS = K_4(1/C) - K_5\sqrt{1/C}\sqrt{1/A}.$$

If this relation is plotted as shown in Figure 3 (dotted line), by evaluating the constants from experimental data, it will be noted that the first term corresponds to the curve of fiber strength *vs.* reciprocal count; and then, if the second term is added (with its negative sign), it yields a curve which closely resembles that of the yarn strength *vs.* reciprocal count for the spinnable range.

The lower end of the curve cannot be defined theoretically or experimentally because it was assumed in the above derivation that ΔR is small compared to R, which would not be true for very fine counts; and, in practice, the balloon tension with irregularity of the yarn actually results in yarn breakage before the idealized limitation is reached. However, with special techniques, it is understood that very fine counts in the region 400's–500's have been spun which would be finer than the intercept of the experimental line extrapolated to the zero axis.

In the spinnable range, both the calculated and experimental curves are very close to straight lines, both curves fall away from the fiber curve in the same manner, and the value K is then interpreted as the extrapolated intercept of the curve of yarn strength *vs.* reciprocal count on the yarn-strength axis.

Conclusion

The skein strength of any count for a spinnable cotton yarn may be predicted by measuring the fineness of the cotton fibers concerned and then spinning one count of (preferably) a coarse yarn under optimum conditions. The skein strength of the count and the fineness can then be substituted into formula (4) to predict the strength of any other count.

Acknowledgments

The authors wish to acknowledge the interest and helpful comments of Drs. H. D. Barker, K. L. Hertel, and C. J. Craven, and the work of Mr. Herbert Hutchens in processing and testing the yarns used.

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(*Manuscript received June 21, 1954.*)

Correction

In the article, "The Influence of Chemical Treatment on the Properties of Wool, Part I: Alkali Solubility as a Measure of Sulfuric Acid Degradation," by J. H. Dusenbury et al., which appeared in the October 1954 issue, on page 895 the last four words of the caption under Figure 6 should have been deleted. The caption should read: "*Effect on fabric abrasion resistence of H_2SO_4 treatments.*"

Letters to the Editor

Short communications in the form of Letters to the Editor are intended to provide prompt publication of significant new research results and to permit an exchange of views on papers previously published in the JOURNAL. These communications are not submitted to formal review as are research papers, and the editors do not assume any share of the author's responsibility for the information given or the opinions expressed. When work previously published in the JOURNAL is the subject of critical comment, the authors of the original paper are given an opportunity to submit a reply, which will be published concurrently when possible.

Moisture and Strength Relations of Decorticated Kenaf Fabric

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANIZATION
Plant Fibre Section
Melbourne, Australia
September 27, 1954

To the Editor
TEXTILE RESEARCH JOURNAL

Dear Sir:

Some interest has been shown in the trade in the use of decorticated kenaf as a substitute for jute. Therefore, the results of the investigation reported below may be of service to readers of Textile Research Journal.

Effects of atmospheric conditions on moisture regains and tensile breaking loads of various textile fabrics are recorded in the relevant literature. They indicate corrections necessary in deriving regain and strength values at conditions other than those employed during laboratory testing. These corrections are important to the manufacturer who is obliged to comply with specifications laid down by a prospective buyer.

There have been some investigations, for jute products, of the relations involved [1, 2, 4] but apparently none for kenaf (*Hibiscus cannabinus* L.), a jute-substitute species.

The object of the investigation described has been to obtain data for a fabric made from decorticated kenaf, as a step towards establishing generally applicable correction data for fabrics of this type.

Experimental

The fabric investigated was made from decorticated kenaf produced in New Guinea. It consisted of 14-lb. (jute count) warp yarns and 44-lb. weft yarns. A simple 2:1 twill weave of 10.5 double warp threads per inch and 8.5 single weft threads per inch gave a canvas weighing 27 oz./sq. yd. Test methods, with the exception of the 12-in. test length employed during strength determinations,* were in accordance with A.S.T.M. Standards on Textile Materials.

Moisture Determinations

Canvas strips were cut 1.5 in. wide and 16 in. long. They were preconditioned in an oven at 50° C to ensure that subsequent conditioning brought the samples to equilibrium from the dry side, *i.e.*, by adsorption. The strips were conditioned for 24 hrs. in an airtight cabinet in which temperatures were thermostatically controlled at 20° and 40° C ($\pm$ 1.5°) in turn, and relative humidities of 35, 50, 65, and 80% ($\pm$ 2%) were obtained by forced circulation of air over saturated solutions of various salts. Actual cabinet conditions were measured by means of dry- and wet-junction thermocouples.

Further strips were preconditioned over water in sealed jars in the oven at 50°C and conditioned to 65% R.H. at 20°C. These samples approached equilibrium moisture regain from the wet side, *i.e.*, by desorption.

After conditioning, the samples were oven dried at 105°C to constant weight. To assist in correcting for oil losses during oven drying, 48-hr. Soxhlet extractions with sulfuric ether were carried out on specimens which had been oven dried and on others which had not been oven dried.

Strength Tests

Further canvas strips were cut 1.5 in. wide and 16 in. long in both the warp and weft directions. The warp and weft strips were frayed down to a

* This test length was in accordance with the methods of the Australian Standards Association.

width of, respectively, 10 double warp threads and 8 single weft threads. The strips were preconditioned at 50°C and conditioned to relative humidities of 35, 50, 65, and 80% at 20° and 40°C. The tensile breaking loads of the strips were determined on a pendulum-type machine, the initial test length between the clamps being 12 in.

Results

The Soxhlet extractions showed that the weight of an oven-dried specimen (not extracted) and the weight of ether solubles lost during oven drying were in the ratio of 94.9:1. Crude moisture regain as

$$\frac{\text{total wt. loss during oven drying}}{\text{oven-dried wt.}} \times 100$$

may therefore be corrected by employing the formula

$$\text{Corrected regain} = \frac{(\text{crude regain} \times 94.9) - 100}{95.9}.$$

Over the range of atmospheric conditions involved, crude regains exceeded corrected regains by 1.1–1.2%

Effects of Atmospheric Conditions on Moisture Regains

Figure 1 records regains under the various atmospheric conditions involved. Regains recorded are means of three determinations. The curves are similar to those for cellulosic substances generally.

Correction of regains to allow for oil loss during oven drying results in curves of virtually the same shape but nearer to the x axis by a distance equivalent to approximately 1.2% regain on the y axis.

Regain increases per unit increase of relative humidity were higher with the kenaf fabric than with jute fiber [1]. The difference between adsorbing and drying regains at 20°C and 65% R.H. was also greater with the kenaf fabric.

Effects of Relative Humidity and Regain on Breaking Load

Figures 2 and 3 record tensile breaking loads at the relative humidities and regains involved. Breaking loads are means of eight tests. The curves are generally similar to those for fabrics of other cellulosic fibers such as flax and cotton.

Correction of regains to allow for oil loss during oven drying results in curves of virtually the same

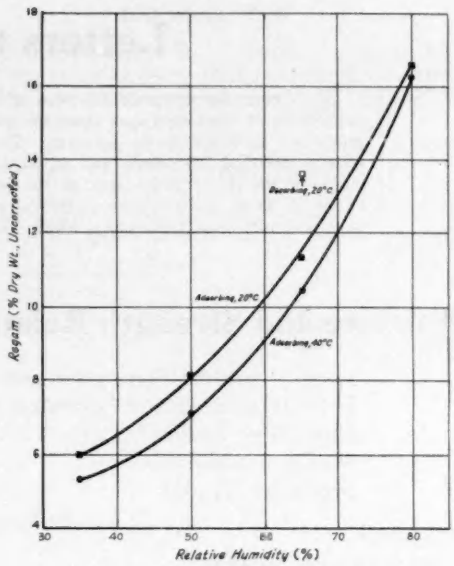

FIG. 1. *Relative humidity-regain curves.*

slope as in Figure 3 but nearer to the y axis by a distance equivalent to approximately 1.2% regain on the x axis.

There is some evidence of decrease of strength of jute products at the higher humidities [2, 4]. There is little indication in Figures 2 and 3 of a corresponding decrease with the kenaf fabric.

Mean breaking loads of oven-dry weft and warp strips were, respectively, 230 and 194 lbs. Rate of increase of breaking load for each increase of percentage regain of 1, expressed as a percentage of oven-dry breaking loads, were therefore 1.3 and 0.6 for weft and warp strips, respectively. The corresponding value, given by Garner [3] for correcting strength values of jute fabrics to required regains, is 2.5.

Conclusion

Moisture and strength relations of the kenaf fabric examined were generally similar to those of other natural cellulose fabrics. Some differences of shape and slope of corresponding curves were observed, and these require confirmation for further kenaf fabrics.

The relations recorded may be employed tentatively for estimating regains and strengths at conditions other than those employed during testing.

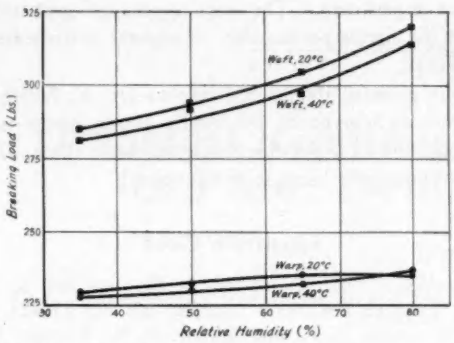

FIG. 2. *Relative humidity-breaking load curves.*

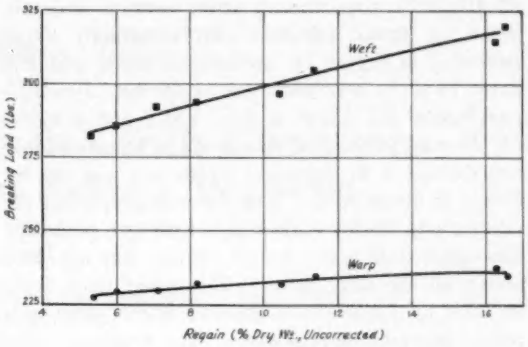

FIG. 3. *Regain-breaking load curves.*

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W. SHEPHERD

Structure of Jute Hemicellulose

INDIAN CENTRAL JUTE COMMITTEE
Technological Research Laboratories
Calcutta, India
October 28, 1954

To the Editor
TEXTILE RESEARCH JOURNAL

Dear Sir:

The major constituent of jute hemicellulose has been shown [1, 2] to be a methyluronic acid linked with xylose units; from the experimental facts then available 3-methylglucuronic acid was considered to be most probable. This has now been confirmed by methylating exhaustively the methylaldobiuronic acid isolated from jute hemicellulose *I* (methoxy content 48.85%), reducing this methylated compound in ether solution with lithium aluminium hydride, hydrolyzing the reduced product, and detecting 2,3,4-trimethylglucose in the hydrolysate by paper partition chromatography against 2,3,4-trimethylglucose as reference substance.

Methylaldobiuronic acid was reduced with lithium aluminium hydride in tetrahydrofuran solution following the procedure of Whistler et al. [3], and the product was hydrolyzed with 5% sulfuric acid on a boiling water bath for 6 hrs. The hydrolysate was freed from acid by passing through Amberlite

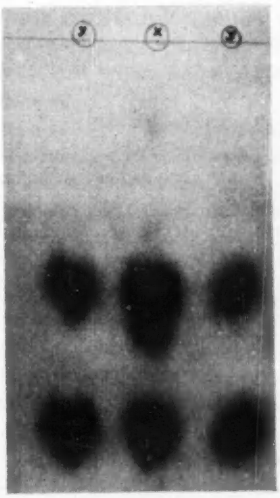

FIG. 1.

IR 4B(OH), concentrated under vacuum, and subjected to paper partition chromatography (spot marked X in Figure 1). *n*-Butanol, acetic acid, and water (4:1:5) was employed as solvent; 3-methyl-α-D-glucose (L. Light & Co., Ltd.) and D-xylose (E. Merck) were used as references (spot in duplicate marked Y in Figure 1). The test was run for 43 hrs. at about 30°C. The chromatograph was developed with freshly made aniline hydrogen phthalate. The upper dark spots are for xylose; they appeared brown on the filter paper. The lower thick spots are due to 3-methyl-α-D-glucose, which were pale yellow just after development. The R-xylose values for the reference substance 3-methyl-α-D-glucose and the unknown sugar derivative in the hydrolysate have been found to be 1.315 and 1.311, respectively. This has also been confirmed using *n*-butanol, ethanol, water, and ammonia (40:10:49:1) as solvent in the above experiment. The faint uppermost spot under X in the figure presumably represents unhydrolysed aldobiose.

Our grateful thanks are due to Dr. F. Smith of Minnesota University for kindly supplying us with a specimen of 2,3,4-trimethylglucosan, which, after hydrolysis, was used as a reference.

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P. C. DAS GUPTA
P. B. SARKAR

INDUSTRIAL SECTION

Graphical Relationships in Cloth Geometry for Plain, Twill, and Sateen Weaves

Louis Love*

Formerly Technologist, Quartermaster Research and Development Laboratories, Philadelphia, Pennsylvania

Prefatory Note

In the seventeen years since the publication of F. T. Peirce's "The Geometry of Cloth Structure" [1], many textile engineers have checked the assumptions upon which the geometric theory is based. Their findings have reflected favorably on Peirce's physical and analytical reasoning. In many cases it was found advisable to extend the original geometric relationships to include woven structures other than those dealt with explicitly in Peirce's writings. The following paper by Mr. Louis Love serves as a useful extension of Peirce's consideration of the maximum weavability of plain weaves. Based on his own observations of fabric cross sections, Love establishes lateral compression factors for other than plain weaves. He combines these with appropriate weave factors to arrive at graphical relationships for maximum weavability—presented here in a form of immediate use to the mill designer.

Following Mr. Love's paper, Dr. John Dickson reports on numerous loom tests which serve to illustrate the validity of Love's assumptions, analyses, and computations. It is worth noting that Dickson's experimental data relate to cotton and to other fibers as well. His calculations demonstrate the direct manner of converting from one yarn count system to another, taking into consideration variations in fiber density. The need for such conversions arises from the use of cotton system cover factors in most published studies of cloth geometry.

EDITOR

THE SUBJECT of fabric geometry was formalized in the comprehensive mathematical analyses of F. T. Peirce [1] in 1937. Surprisingly little use has been made of Peirce's work in the practical field of cloth design during the past sixteen years. This delay has been due in part to the mathematical complexities inherent in the relationships between such cloth parameters as threads per inch, yarn count, and crimp. Peirce attempted to alleviate this condition by furnishing extensive tables relating the variables of fabric construction and by proposing both models and graphs to shorten the computations necessary for the design of new materials. Recently, extensive graphical methods have been proposed [2] with a view to eliminating extended calculations and lengthy interpolations from Peirce's tables. A parallel set of graphical techniques has been developed in the textile laboratories of the Quartermaster Corps and has found considerable utility during the past five years. It is the purpose of this paper to make these additional useful graphical tools available to the practicing fabric designer.

In the course of applying Peirce's theories to the design of various fabrics, it was found both necessary and convenient to extend the range of the diagrams presented for plain-weave fabrics and to evaluate their functions in additional weaves. Although Peirce mentioned the effect of weave on maximum setting, the importance of this factor on the physical behavior of a fabric indicated a need for further development. Accordingly, an extensive series of calculations was made in order to provide a graphical presentation of the effect of short float weaves on the tightness of a fabric.

The first case considered was the plain weave in which the ratio β of filling-yarn diameter to warp-yarn diameter varied significantly. The practical

* Present address: 5339 Angora Terrace, Philadelphia 43, Pennsylvania.

question asked in the design of many military fabrics in the past ten years has been, "If the warp cover factor* is prescribed for reasons of water or wind resistance, what is the maximum number of picks weavable in such a fabric?" Peirce has indicated that, for closest plain weaves,

$$\sqrt{1 - (p_1/D)^2} + \sqrt{1 - (p_2/D)^2} = 1, \quad (1)$$

and that

$$K_1 = 28/(1 + \beta) \div (p_1/D); \quad (2)$$

$$K_2 = 28\beta/(1 + \beta) \div (p_2/D), \quad (3)$$

where p_1, p_2 are the spacings in inches between warp and filling threads; K_1, K_2 are warp and filling cover factors; β is the ratio of filling to warp diameters; and D is the sum of warp and filling yarn diameters in inches. By combining the above equations one obtains the expression

$$\sqrt{1 - \left[\frac{28}{(1 + \beta)K_1}\right]^2} + \sqrt{1 - \left[\frac{28\beta}{(1 + \beta)K_2}\right]^2} = 1, \quad (4)$$

indicative of the relationship of K_1, K_2, and β for fabrics jammed in both directions. It is now evident that the answer to the question stated above may be determined uniquely, provided that the value β is specified. Peirce took the case of $\beta = 1$ and plotted K_1 versus K_2 for the closest plain-weave constructions. It has been found necessary in many Quartermaster Corps studies to work with β values differing significantly from $\beta = 1$, and so an extension of Peirce's graph has been made. This extension is presented in Figure 1.

A corollary to the use of Figure 1 indicated above is the quick graphical answer to the question, "What is the relative tightness in warp and filling direction in a given fabric?" Warp tightness may be expressed as the ratio of actual warp cover factor to maximum warp cover factor, as determined from Figure 1, when the filling cover factor and the ratio of yarn diameters are specified. Likewise, the relative filling tightness is expressed as the ratio of actual filling cover factor to maximum filling cover factor as determined from Figure 1. The over-all value of tightness, useful in studies of the mechanical properties of fabrics, is expressed as

$$\text{tightness} = \frac{\text{sum of actual warp and filling cover factors}}{\text{sum of theoretically maximum cover factors}}. \quad (5)$$

The maximum cover factors for other yarns in addition to cotton are given for the reader's convenience in the legend of Figure 1 (and also of Figures 3 to 6, inclusive). These cover factors have been calculated from the specific volume of the material v, based on Peirce's formula

$$v = 1.021 y N d^2, \quad (6)$$

where N is the number of units (hanks) of length and y is yards in a pound of yarn of diameter d in inches. Peirce assumed a constant value of 1.1 for the apparent specific volume of the cotton yarn under the compression of the weave structure. So that comparisons can be made among the various fibers, v is here replaced by the inverse product of the specific gravity of the fiber (ψ) and the yarn packing coefficient (ϕ). Thus for the inverse yarn-numbering system, equation (6) becomes

$$1/d = \sqrt{1.021 y N \psi \phi}, \quad (7)$$

and for the direct system

$$1/d = \sqrt{1.021 y / N_d \psi \phi}, \quad (8)$$

where d is again expressed in inches while y is expressed in yards/pound. For the direct denier system, y = 4,464,528 yds./lb. The packing coefficient ϕ has been estimated to be approximately 0.6.

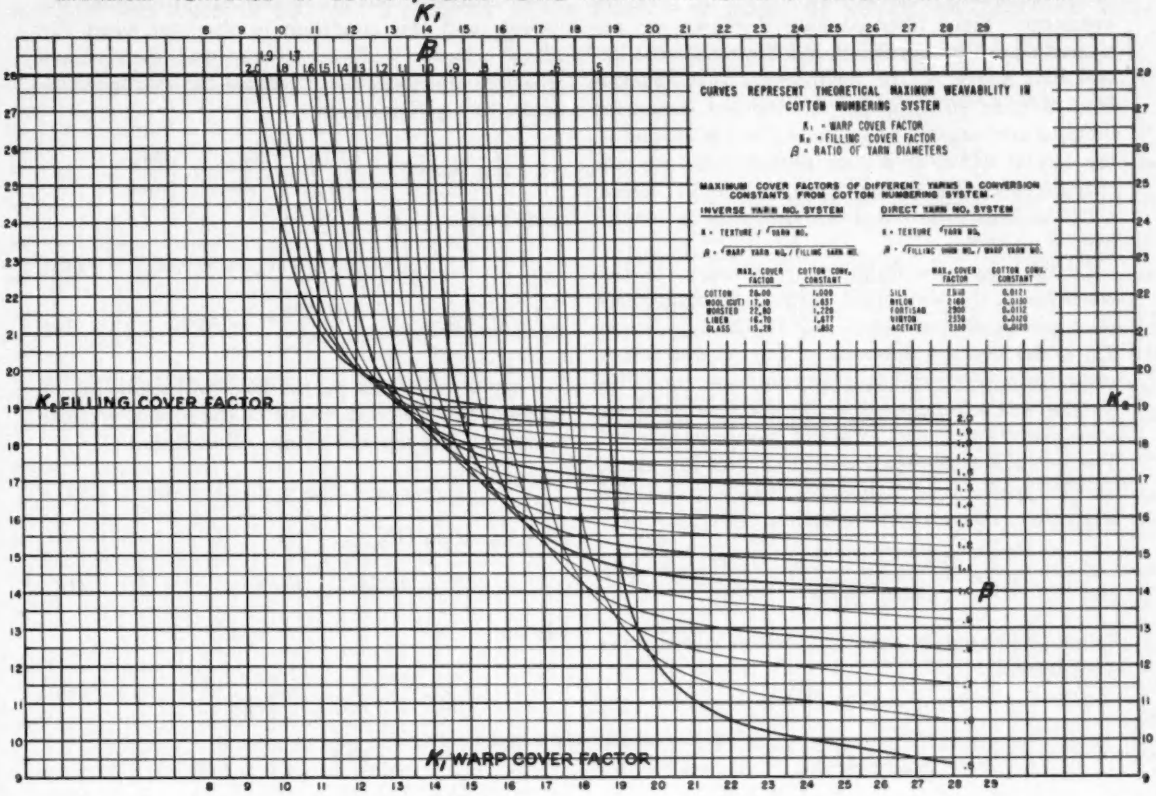
When other than plain weaves are studied, the quantities p_1 and p_2 of equation (1) apply to the local spacings between yarns at the interlacings of warp and filling. The local spacings between warp and filling at points of *no interlacing*, that is, at float locations, will in general be less than the local spacing at points of interlacing. Since quantities K_1 and K_2 represent average cover factors, relationships (2) and (3) must be altered to account for the weave factor and the degree of yarn flattening and/or overriding which takes place in other than plain weaves. Weave factor, M, is defined as:

$$M = \frac{\text{number of threads per repeat of weave}}{\text{number of interlacings per repeat of weave}}. \quad (9)$$

Thus, $M = 1$ characterizes the plain weave; $M = 1.5$, a 2/1 twill; $M = 2$, a 2/2 twill, a 3/1 twill, a 4-harness satin, or the warp yarns of an oxford

* Defined by Peirce (for the inverse yarn-numbering system) as the ratio of the threads per inch to the square root of the yarn number.

FIG. 1
MAXIMUM TEXTURES OF COTTON, PLAIN WEAVE FABRICS IN TERMS OF COVER FACTORS & BETA


K_1
β
CURVES REPRESENT THEORETICAL MAXIMUM WEAVABILITY IN COTTON NUMBERING SYSTEM
K_1 = WARP COVER FACTOR
K_2 = FILLING COVER FACTOR
β = RATIO OF YARN DIAMETERS
MAXIMUM COVER FACTORS OF DIFFERENT YARNS & CONVERSION CONSTANTS FROM COTTON NUMBERING SYSTEM.
INVERSE YARN NO. SYSTEM
DIRECT YARN NO. SYSTEM
K_2 FILLING COVER FACTOR
K_1 WARP COVER FACTOR

weave; $M = 2.5$, a 3/2 twill, a 4/1 twill, or a 5-harness satin. If the degree of flattening is overlooked for the moment, the local spacing between warp yarns at the interlacing of warp and filling can be shown to equal

$$p_1 = Mp_{a1} - (M - 1)d_{ca1}, \qquad (10)$$

where d_{ca1} is the *original* average lateral diameter of the warp yarn. If lateral compression is now considered, the expression for the local spacing p_1 is somewhat modified by the introduction of d_{ca1}, the *new* average lateral diameter of the warp yarns. The new diameter d_{ca1} averages both compressed and uncompressed lateral diameters pictured in Figure 2 for several different weave repeats.

$$p_1 = M(p_{a1} - d_{ca1}) + d_{oa1}. \qquad (11)$$

When yarns of average twist or softness are woven in fabrics of other than plain weave, it has often been observed that maximum weavable cover factors exceed the value 28. The reason for this becomes evident in microscopic examination of fabric cross sections, which show considerable lateral compression in yarns beneath the weave floats. The extent of this compression will, of course, vary with the twist of the yarn, the fiber cross sections, and the actual transverse compression between yarns. For purposes of computation we may assume (1) that the yarn compression in a fabric woven to maximum tightness produces a change in the shape of the yarn section, but does not alter the fiber packing density; and (2) that complete flattening takes place in that half of the yarn which contacts a neighboring yarn under a single float, *i.e.*, that the original semicircle of the yarn half section becomes a rectangle after compression. This definition of beneath-float compression (pic-

tured in Figure 2A) satisfies the condition of actual fabric geometry observed in numerous practical instances. Since fiber packing densities are unaltered during compression, it follows that the lateral half width of the compressed yarn changes from $d/2$ to $\pi d/8$, while the vertical dimension remains unchanged. As seen in Figures 2A and B, the lateral width of a yarn flattened on one side only becomes $(1 + \pi/4)d/2$, while the entire lateral width of a yarn flattened on both sides is reduced from d to $\pi d/4$.

In the case of a filling float passing over two warp yarns, the horizontal width of all warp yarns per repeat is seen in Figure 2A to be $2.78d_{oa1}$, where d_{oa1} is the average diameter of the original yarns, subscript a being the average condition computed for the weave repeat, subscript o the original uncompressed state, and subscript 1 indicating warp. The average compressed warp diameter calculated for the repeat of the 2/1 weave is $2.78d_{oa1}/3$. The warp cover factor is, by definition,

$$K_1 = \frac{\text{threads per inch}}{\sqrt{\text{warp count}}} = \frac{\text{TPI}}{\sqrt{N_1}}. \qquad (12)$$

Peirce [1] has shown that for cotton yarns under compression

$$d = 1/28\sqrt{N}. \qquad (13)$$

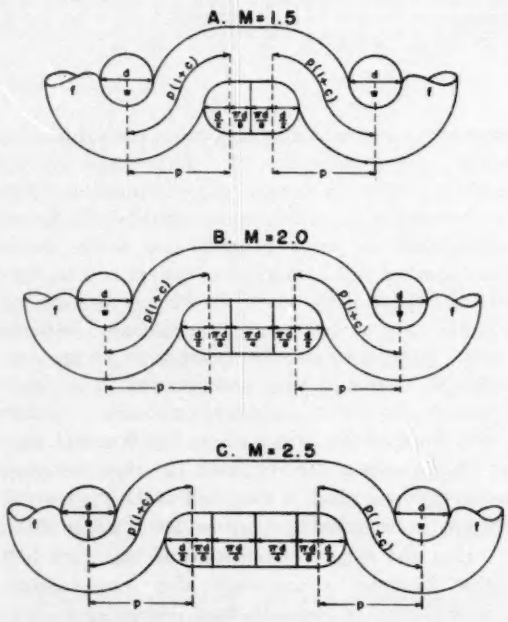


FIG. 2. *Yarn compression beneath the float.*

The maximum average warp cover factor will occur when adjacent ends are in contact throughout the repeat, and this condition is observed when the filling crimp is reduced to zero and the average spacing between ends just equals the average compressed warp diameters.

$$K_{a1}\ (\text{max.}) = \frac{\text{TPI}_{a1}}{\sqrt{N_{a1}}} = \frac{28d_{oa1}}{p_{a1}} = \frac{28d_{oa1}}{d_{ca1}}, \qquad (14)$$

and, since

$$d_{ca1} = (2.78/3)d_{oa1} = 0.93d_{oa1}, \qquad (15)$$

$$K_{a1}\ (\text{max.}) = \frac{(3)(28)d_{oa1}}{2.78d_{oa1}} = 30.2. \qquad (16)$$

We can now express p_1, the local warp spacing, in terms of the fabric scale unit D, the sum of vertical diameters in warp and filling. Recall that

$$D = d_{oa1} + d_{oa2} = d_{oa1}(1 + \beta); \qquad (17)$$

from equation (15),

$$D = 1.08d_{oa1}(1 + \beta), \qquad (18)$$

whence

$$\frac{p_1}{D} = \frac{M(p_{a1} - d_{ca1}) + d_{oa1}}{1.08d_{oa1}(1 + \beta)}, \qquad (19)$$

$$\frac{p_1}{D} = M\frac{\left(\dfrac{30.2}{K_{a1}} - 1\right) + 1.08}{1.08(1 + \beta)}, \qquad (20)$$

since from equation (14)

$$K_{a1} = \frac{28d_{oa1}}{p_{a1}} = \frac{28(1.08)d_{ca1}}{p_{a1}} = \frac{30.2d_{ca1}}{p_{a1}}. \qquad (21)$$

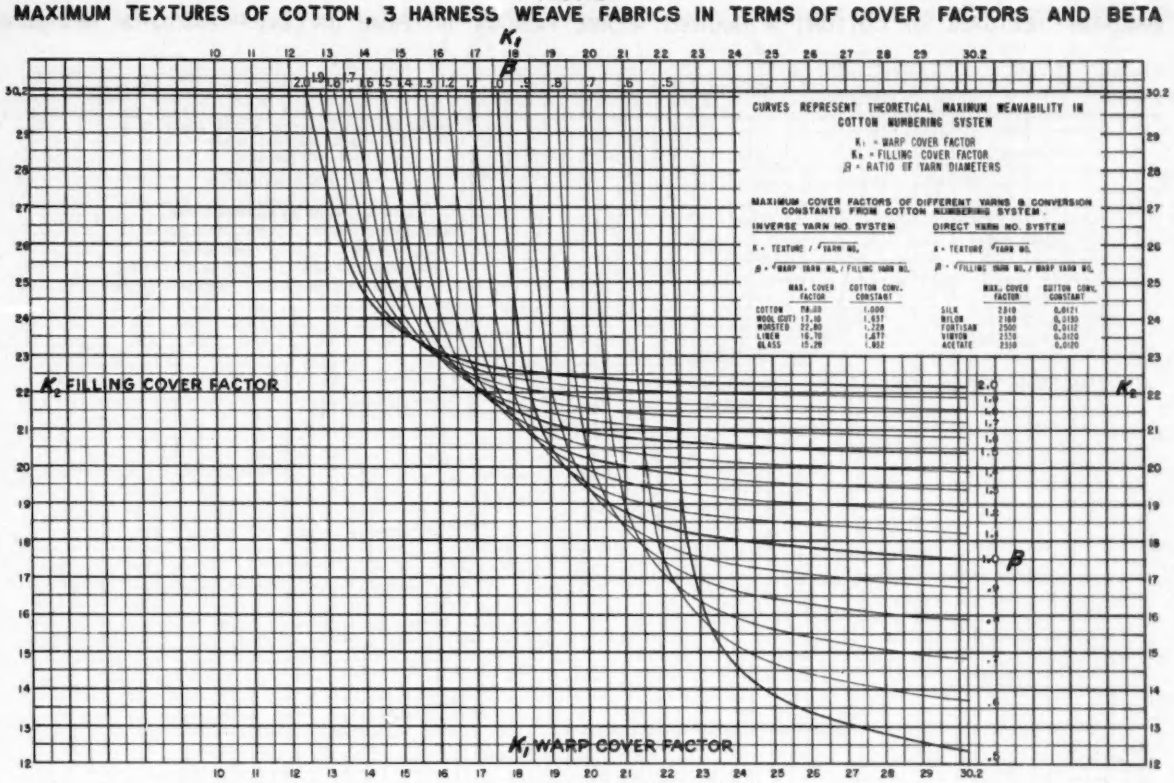
Corresponding to equation (20) we have

$$\frac{p_2}{D} = \frac{\left[M\left(\dfrac{30.2}{K_{a2}} - 1\right) + 1.08\right]\beta}{1.08(1 + \beta)}. \qquad (22)$$

Substituting equations (20) and (22) in equation (1), one arrives at

$$\sqrt{1 - \left[\frac{M\left(\dfrac{30.2}{K_{a1}} - 1\right) + 1.08}{1.08(1 + \beta)}\right]^2} + \sqrt{1 - \left[\frac{\left(M\left[\dfrac{30.2}{K_{a2}} - 1\right] + 1.08\right)\beta}{1.08(1 + \beta)}\right]^2} = 1. \qquad (23)$$

FIG. 3
MAXIMUM TEXTURES OF COTTON, 3 HARNESS WEAVE FABRICS IN TERMS OF COVER FACTORS AND BETA


CURVES REPRESENT THEORETICAL MAXIMUM WEAVABILITY IN COTTON NUMBERING SYSTEM
K_1 = WARP COVER FACTOR
K_2 = FILLING COVER FACTOR
β = RATIO OF YARN DIAMETERS
MAXIMUM COVER FACTORS OF DIFFERENT YARNS & CONVERSION CONSTANTS FROM COTTON NUMBERING SYSTEM
INVERSE YARN NO. SYSTEM
DIRECT YARN NO. SYSTEM
MAX. COVER FACTOR
COTTON CONV. CONSTANT
COTTON 28.28 1.000
WOOL (CUT) 17.10 1.657
WORSTED 22.80 1.239
LINEN 16.70 1.677
GLASS 15.29 1.852
SILK 2310 0.0121
NYLON 2160 0.0130
FORTISAN 2500 0.0112
VINYON 2150 0.0130
ACETATE 2310 0.0120
K_2 FILLING COVER FACTOR
K_1 WARP COVER FACTOR
K_2
β

Equation (23) serves as the principal basis for construction of Figure 3, in which the relationship between K_{a1} and K_{a2} and β is presented graphically. Comparison of Figures 3 and 1 for given values of warp cover factor and β shows the filling packing limit for the twill weave ($M = 1.5$) to be much higher than for the plain weave. Similarly, it can be shown that for given values of K_{a1}, K_{a2}, and β the relative tightness one obtains in a plain weave is much higher than that in a twill weave. These qualitative facts are known to the textile technologist. The value of the graphs, however, lies in the quantitative values which may now be readily determined.

In the case of a 3/1 (or a 2/2) twill, *i.e.*, when $M = 2.0$, the central yarns beneath the float will be compressed to the width $\pi d/4$, as seen in Figure 2B. The average compressed diameter now becomes

$$d_{ca1} = 3.57 d_{oa1}/4 = 0.89 d_{oa1}, \tag{24}$$

or

$$d_{oa1} = 1.12 d_{ca1}. \tag{25}$$

It follows that

$$K_{a1} = \mathrm{TPI}/\sqrt{N} = 28 d_{oa1}/p_{a1} = 31.4 d_{ca1}/p_{a1}, \tag{26}$$

whence

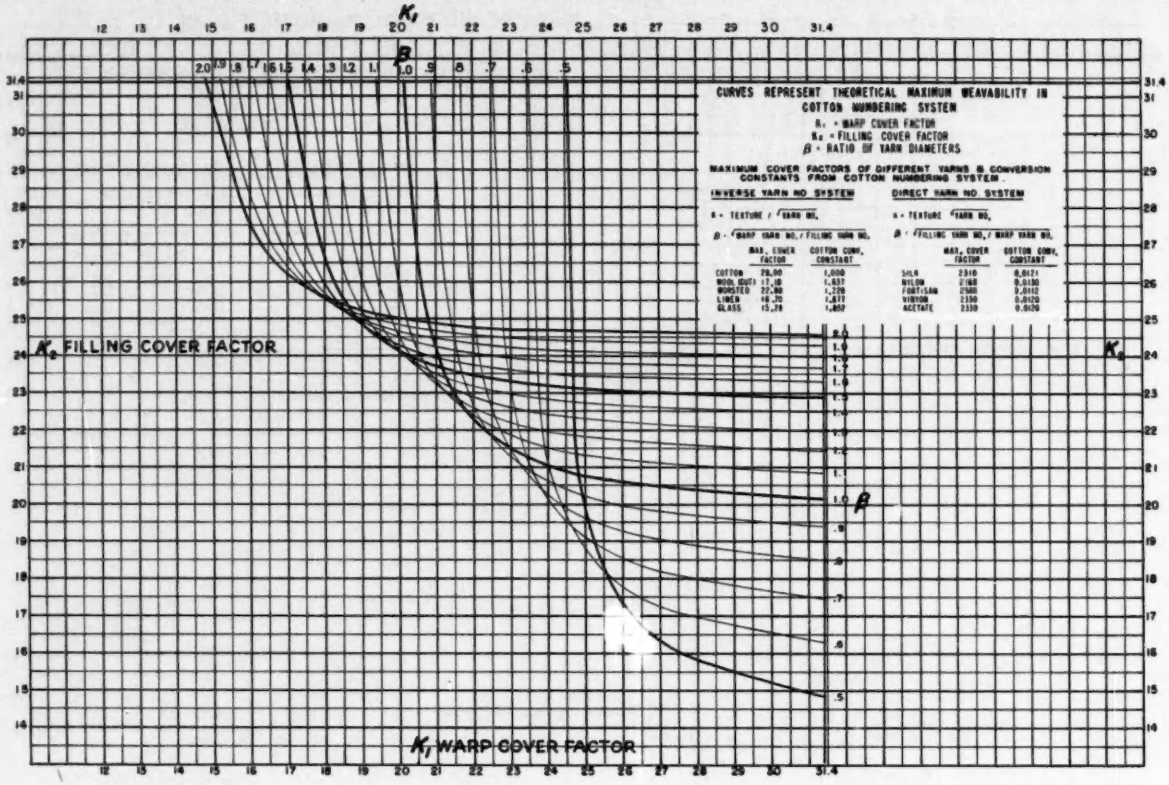
$$\frac{p_1}{D} = \frac{M\left(\frac{31.4}{K_1} - 1\right) + 1.12}{1.12(1+\beta)}; \tag{27}$$

$$\frac{p_2}{D} = \frac{\left[M\left(\frac{31.4}{K_2} - 1\right) + 1.12\right]\beta}{1.12(1+\beta)}. \tag{28}$$

From equations (27) and (28) the relationship corresponding to equation (23) leads to the graphical presentation of Figure 4 (for 3/1 or 2/2 fabrics; *i.e.*, $M = 2.0$). Where $M = 2.5$ we may have

FIG. 4

MAXIMUM TEXTURES OF COTTON, 4 HARNESS WEAVE FABRICS IN TERMS OF COVER FACTORS AND BETA


K_1
β
K_2 FILLING COVER FACTOR
K_1 WARP COVER FACTOR
CURVES REPRESENT THEORETICAL MAXIMUM WEAVABILITY IN COTTON NUMBERING SYSTEM
K_1 = WARP COVER FACTOR
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β = RATIO OF YARN DIAMETERS
MAXIMUM COVER FACTORS OF DIFFERENT YARNS & CONVERSION CONSTANTS FROM COTTON NUMBERING SYSTEM
INVERSE YARN NO SYSTEM
DIRECT YARN NO SYSTEM

either a 4/1 or a 3/2 weave. From Figure 2C the average compressed diameter for $M = 2.5$ is seen to be:

$$d_{c_{a1}} = 0.87 d_{o_{a1}} \tag{29}$$

or

$$d_{c_{a1}} = 1.15 d_{c_{a1}}, \tag{30}$$

whence

$$K_{a1} = 28(1.15) d_{c_{a1}}/p_{a1} = 32.2 d_{c_{a1}}/p_{a1} \tag{31}$$

and

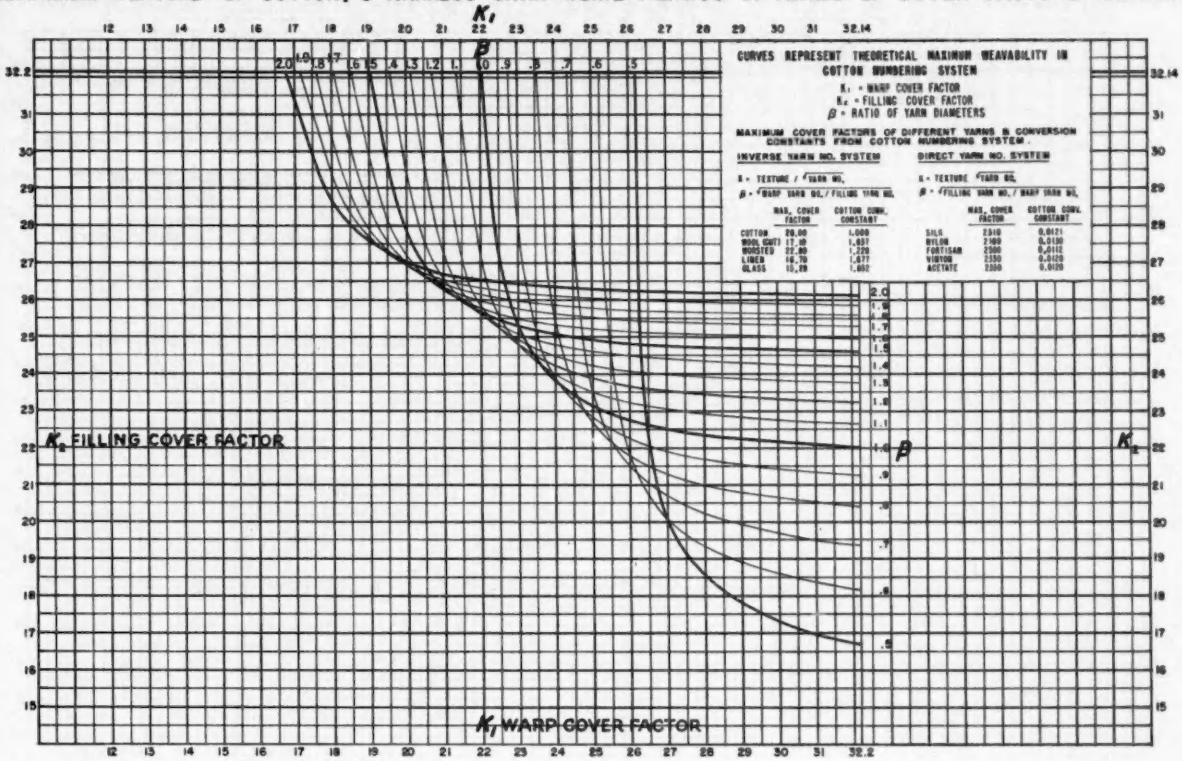
$$\frac{p_1}{D} = \frac{M\left(\frac{32.2}{K_1} - 1\right) + 1.15}{1.15(1+\beta)}; \tag{32}$$

$$\frac{p_2}{D} = \frac{\left[M\left(\frac{32.2}{K_2} - 1\right) + 1.15\right]\beta}{1.15(1+\beta)}. \tag{33}$$

Substitution of equations (32) and (33) in equation (1) leads to the geometric relationship between K_{a1} and K_{a2} for maximum weavable fabrics of a 4/1 or 3/2 twill construction (including sateens). This function is plotted in Figure 5. Again, comparison of Figures 3, 4, and 5 with the curves relating K_1 and K_2 for the plain weave (Figure 1) reveals that increasingly greater filling packing limits (for any fixed warp cover factor) occur at higher weave factors. Conversely, if filling covers are arbitrarily fixed, greater warp packing is possible at higher weave factors. Finally, when β, K_1, and K_2 are specified, the relative tightness of a given weave decreases as M increases.

There is little point in extending the indicated modifications of equations (2) and (3) to the weave factors exceeding $M = 2.5$ since it is unlikely that

FIG. 5
MAXIMUM TEXTURE OF COTTON, 5 HARNESS SATIN WEAVE FABRICS IN TERMS OF COVER FACTORS AND BETA

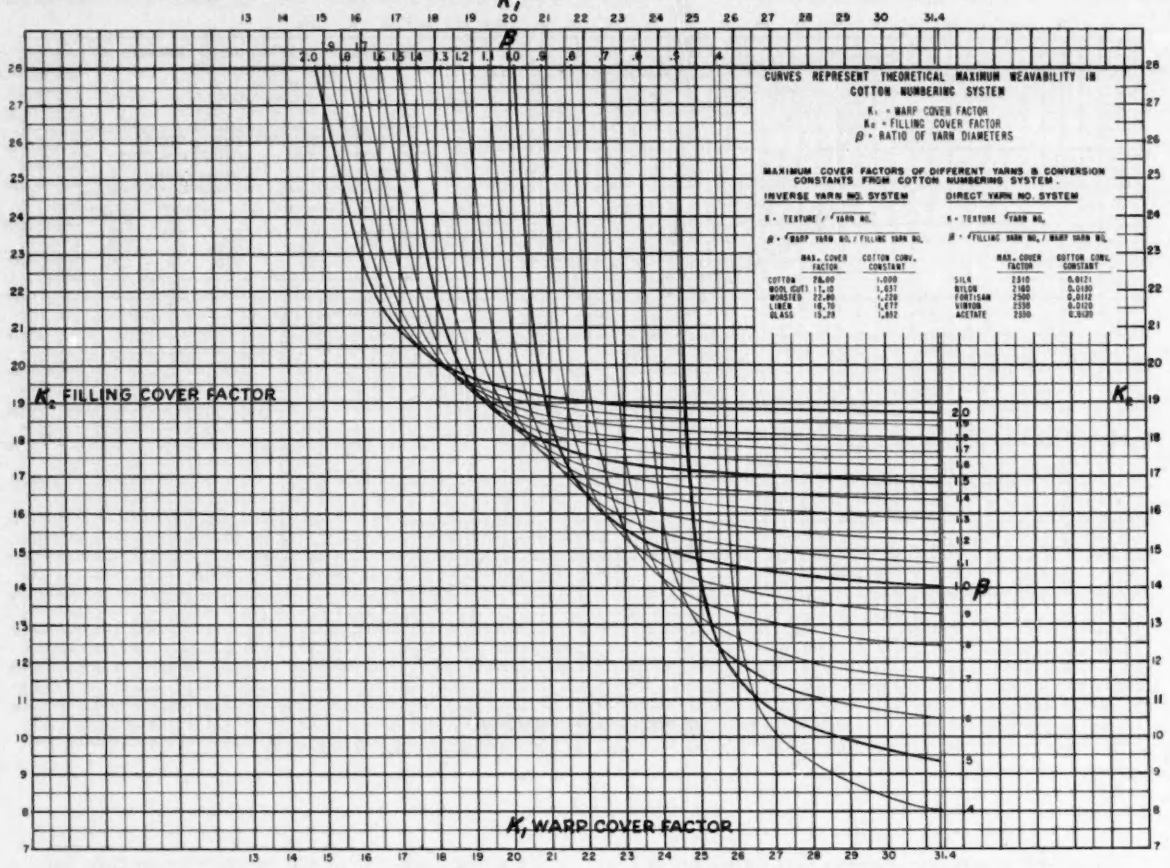

K1
β
CURVES REPRESENT THEORETICAL MAXIMUM WEAVABILITY IN COTTON NUMBERING SYSTEM
K1 = WARP COVER FACTOR
K2 = FILLING COVER FACTOR
β = RATIO OF YARN DIAMETERS
MAXIMUM COVER FACTORS OF DIFFERENT YARNS & CONVERSION CONSTANTS FROM COTTON NUMBERING SYSTEM.
INVERSE YARN NO. SYSTEM
DIRECT YARN NO. SYSTEM
MAX. COVER FACTOR
COTTON CONV. CONSTANT
COTTON 28.00 1.000
WOOL (CUT) 17.10 1.637
WORSTED 22.80 1.226
LINEN 16.70 1.677
GLASS 10.29 1.602
SILK 23.10 0.8121
RAYON 21.90 0.8130
FORTISAN 21.90 0.8112
VISCOSE 23.30 0.8120
ACETATE 23.00 0.8120
K2 FILLING COVER FACTOR
K1 WARP COVER FACTOR

the simple geometric assumptions indicated in Figure 2 are met for floats longer than 4-cross yarns. Indeed, in applying the relationships presented in Figure 5 for the weave factor 2.5, the technologist must insure compliance of the actual structure with the geometric assumption of lateral compression.

To make the graphical solutions outlined above generally applicable, we must include a sample of those constructions which possess different weave factors in the warp and filling directions. The most common material of this category is the oxford weave, in which two warp yarns interlace as one in an otherwise plain weave, resulting in weave factors $M_1 = 2.0$ and $M_2 = 1.0$. To obtain a relationship between K_1, K_2, and β for an oxford weave one must substitute equations (27) and (3) for p_1 and p_2, respectively, in equation (1). The result of this substitution is plotted in Figure 6.

This discussion of fabric geometry has thus far been concerned with the projected cover of warp and filling yarns and with the relative tightness of each yarn system. Cover factors, it has been pointed out, are of primary interest in studies of the permeability of fabrics to air and water. Tightness factors, on the other hand, relate to a wide variety of mechanical fabric properties including wear resistance, flexibility, drape, and dimensional stability. Note, however, that cover and tightness factors pertain principally to the two-dimensional structure of the fabric. To round out the consideration of fabric properties, it is essential to deal with the third fabric dimension, that of thickness, or "wave height" of the yarn systems. Peirce has pointed out that the thickness of a fabric equals the sum of the wave height and diameter of warp or filling yarns, whichever sum is larger. The thick-

FIG. 6
MAXIMUM TEXTURES OF COTTON, OXFORD WEAVE FABRICS IN TERMS OF COVER FACTORS & BETA


CURVES REPRESENT THEORETICAL MAXIMUM WEAVABILITY IN COTTON NUMBERING SYSTEM
K1 = WARP COVER FACTOR
K2 = FILLING COVER FACTOR
β = RATIO OF YARN DIAMETERS
MAXIMUM COVER FACTORS OF DIFFERENT YARNS & CONVERSION CONSTANTS FROM COTTON NUMBERING SYSTEM.
INVERSE YARN NO. SYSTEM
DIRECT YARN NO. SYSTEM
K2 FILLING COVER FACTOR
K1 WARP COVER FACTOR
β

ness of fabric structures is directly related to their insulating qualities and their cushioning or softness characteristics. On the other hand, the difference between the wave height and diameter sum for warp and filling systems determines the absolute projection of one yarn system above the other at the fabric surface. This projection significantly influences the appearance and the wearing qualities of the fabric.

Peirce has shown the approximate relationship between wave height h, the fractional crimp c, and the yarn spacings p,

$$h_1 = 1.36 p_2 \sqrt{c_1}, \qquad (34)$$

to hold over a wide range of fabric constructions. It must be noted, however, that the values of crimp and thread spacings in equation (34) apply to the plain weave or to the unit cell of the twill weave where interlacing takes place. Peirce plotted equation (34) in terms of h_1/D and p_2/D, as illustrated in the lower left hand corner of Figure 7 (the radiating lines). The curve at the extreme left represents the condition of maximum weavability and is plotted from the requirement

$$\cos\theta_1 + \cos\theta_2 = 1, \qquad (35)$$

where θ is the maximum inclination of a given yarn to the fiber plane. Recall the additional require-

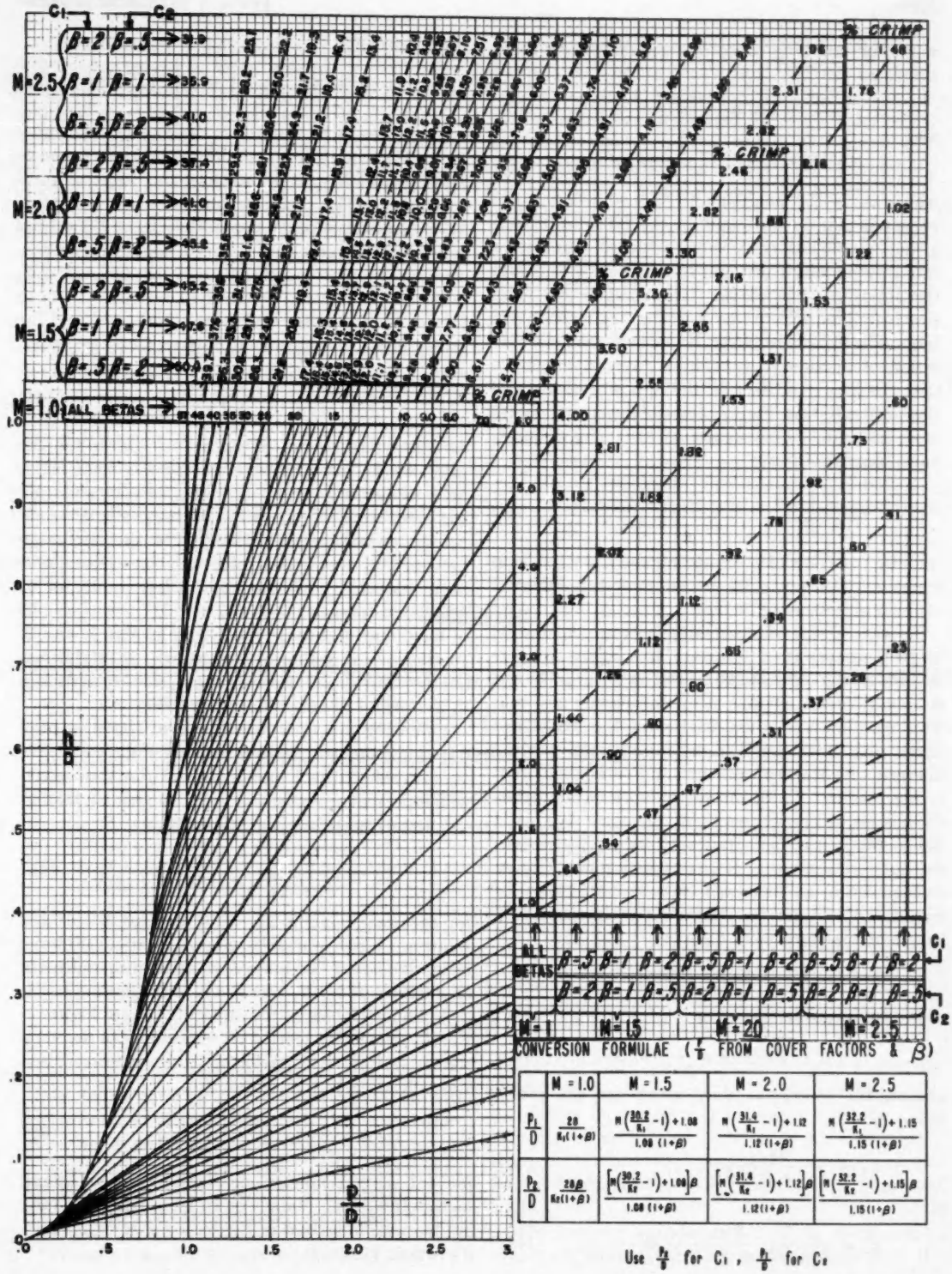


FIG. 7. YARN DISPLACEMENT OF VARIOUS WEAVE FABRICS IN TERMS OF YARN SPACING AND CRIMP

ment for jamming in both warp and filling direction, *i.e.*,

$$h_1/D = \cos \Delta_1 \tag{36}$$

and

$$p_2/D = \sin \Delta_2 = \sqrt{1 - \cos^2 \Delta_2}, \tag{37}$$

where Δ_1 is the acute angle formed when a line perpendicular to the plane of the fabric intersects a line joining the centers of two warp yarns separated by a filling yarn, and Δ_2 is the same angle for the opposite set of yarns. These angles are quantitatively identical to Peirce's θ_2 and θ_1, respectively (equation 35). Moreover, if one considers the condition of maximum weavability, it can be shown that the arcs described by the opposing threads of the unit cell (see Figure 2) provide crimp values more accurately represented on the curve of maximum weavability by

$$c_1 = \frac{L_1/D}{p_2/D} - 1 = \frac{\Delta_2 \text{ radians}}{\sin \Delta_2} - 1 \tag{38}$$

than by equation (34). Crimp values plotted from equations (34) and (38) are combined in Figure 7 to form almost straight lines.

To extend the relationships between h_1 and p_2 to twill weaves it is necessary to employ C_1 (pertaining to the entire twill fabric) as a variable, not simply c_1, which pertains to the interlacing unit cell. This modification is essential since the weave designer customarily varies C_1 by appropriately setting his reed width, warp take-ups, and subsequent tentering widths. C_1 for the entire fabric is defined as the excess of actual length of the yarn axis as it lies in the fabric, over its length as projected onto the horizontal plane. If one takes a filling section corresponding to the warp cross-sectional view of Figure 2A, it can be shown that the projected length of the warp yarn L_p in a 2/1 twill is

$$L_{p_1} = 2p_2 + 0.785d_2, \tag{39}$$

while the actual length L_t is

$$L_{t1} = 2p_2(1 + c) + 0.785d_2, \tag{40}$$

whence the fractional warp crimp for the entire weave is

$$C_1 = \frac{2p_2c_1}{2p_2 + 0.785d_2}, \tag{41}$$

or

$$C_1 = \frac{2(p_2/D)c_1}{2(p_2/D) + [0.785\beta/(1 + \beta)]}, \tag{42}$$

since

$$D = d_1 + d_2 = d_2\left(\frac{1}{\beta} + 1\right) = d_2\left[\frac{(1 + \beta)}{\beta}\right]. \tag{43}$$

It follows from the above derivation that equation (42) relates C_1 to c_1 under conditions of *maximum weavability*, and therefore the value of p_2/D in equation (42) must be obtained from equation (22). However, when moderately tight 2/1 fabrics are dealt with, equation (42) still holds with reasonable accuracy provided that the yarns beneath each float are in contact with one another. In such fabrics the yarns are no longer compressed and the factor 0.785 in equation (42) is replaced by unity, and

$$C_1 = \frac{2(p_2/D)c_1}{2(p_2/D) + [\beta/(1 + \beta)]}. \tag{44}$$

In open fabrics the crimp values (both for the plain-weave unit cell and for the 2/1 twill fabric as a whole) will be small. The form of equation (42) indicates that C_1 will always be smaller than c_1; *i.e.*, c_1 may be considered to be the maximum limit of C_1. In Figure 7, the radiating c_1 lines have been relabeled with the appropriate values of C_1 calculated from equation (42) for 3/1 constructions of maximum tightness and for β's of 0.5, 1, and 2. In this way a graphical relationship is established among h_1/D, p_2/D, and C_1 with greatest accuracy in the region of maximum weavability.

Following the procedure described above we may use the geometric assumptions of Figure 2B (reversing subscripts 1 and 2 so that the view given will represent a section at right angles to that of the figure) to deduce the relationship

$$C_1 = \frac{(p_2/D)c_1}{(p_2/D) + [0.785\beta/(1 + \beta)]} \tag{45}$$

for the weave factor $M = 2.0$, *i.e.*, for 3/1 or 2/2 weaves. Cloth crimps based on equation (45) have been calculated for fabrics of maximum tightness at β values of 0.5, 1, and 2, and these are indicated as secondary labels on the radiating lines of Figure 7. Finally, the filling section corresponding to the view shown in Figure 2C furnished the geometric constants leading to the relationship

$$C_1 = \frac{2(p_2/D)c_1}{2(p_2/D) + [2.355\beta/(1 + \beta)]} \tag{46}$$

for 4/1 or 3/2 fabrics corresponding to a weave factor $M = 2.5$. Values of C_1 from equation (46) are likewise indicated in Figure 7 for $M = 2.5$ and β's of 0.5, 1, and 2.

It should be noted that equations (42), (45), and (46) deal with total warp crimp. To calculate filling crimp these same equations may be used, provided that the β over the $(1 + \beta)$ is eliminated. A simpler method of determining filling crimp for the fabric from equations (42), (45), and (46) is to use β' instead of β, where β' is the reciprocal of β. This device permits use of Figure 7 for determination of *both* warp and filling crimps necessary in a wide range of weaves to achieve desired values of wave height and thread spacings.

Acknowledgments

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Finally, warm and sincere thanks are given to friends with whom this work has been discussed, particularly to Mr. Julian S. Jacobs, Editor, Textile Research Journal, and Dr. John B. Dickson, U. S. Rubber Co., for their continued encouragement.

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Practical Loom Experience on Weavability Limits

John B. Dickson*

Textile Division, United States Rubber Company, New York, New York

Author's Note

Any one making a design for a woven fabric naturally wants to be sure in advance that the loom will weave the design. Thus, a practical designer, when first considering the use of Love's weavability graphs, is likely to ask himself: "The geometry may be all right, but how about loom performance? How closely can I expect the loom results to agree with the graph?" If the designer with these questions in mind wants a quick answer he can get it by looking down the columns in the data tables given in this paper. The last column in each table shows the difference between loom performance and graph prediction, a plus difference indicating that the loom outperforms the graph, and a minus that the loom does not come up to the graph. Then he can read the brief summary at the end.

The general answer is that data comparing loom performance with graph limits of weavability show Love's graphs to be useful practical guides to weavability.

Introduction

Mr. Louis Love kindly provided the writer with copies of his weavability graphs before publication; these appear in his paper, "Graphical Relationship in Cloth Geometry for Plain, Twill, and Sateen Weaves," page 1073. Weavability graphs are a "must" for those engaged in serious design of woven fabrics. At the United States Rubber Company continuous use has been made of Mr. Love's graphs, and it can be stated that for anyone having them there is no excuse for arriving at an unweavable design. Without such graphs, this embarrassment has probably been experienced in the best regulated mills.

The question as to the practical use of the graphs which bothered the writer, and to which it is the

* Present address: 135 West 79 St., New York 24, N. Y.

purpose of this article to supply at least a partial answer, is about as follows: The graphs are based on geometrical considerations—a loom has never gone to school and doesn't know geometry—how closely, then, does loom weavability compare with theoretical weavability derived from geometrical considerations?

The assumptions underlying the geometry are: (1) that the yarns are cylindrical, (2) that the bulk density of any cotton yarn is 0.91 g./cc. (Peirce), and (3) that yarns other than cotton can be brought under Peirce's convention for yarn bulk density by the "All-Fiber System" previously introduced by the author [1]. The all-fiber system assumes that other kinds of yarns are as compact as cotton, from which it follows that conventional diameters of yarns other than those of cotton can be computed by taking fiber density into account. The foregoing assumptions may not hold for actual yarns, which is additional reason for verifying the practical utility of the graphs. A compilation of data on loom weavability has been made, as such data have been encountered, and has then been compared with Love's geometrical graphs, as will be shown later in the article. No pretense is made that the literature has been completely covered.

Mr. Love deserves a tribute. In computing and plotting these graphs he has accomplished a prodigious amount of work, which fact he has been too modest to point out. The results have been worth the effort. His weavability graphs are a signal contribution to textile design. Their value is bound to be increasingly appreciated as the graphs are more widely employed for purposes of practical design.

Discussion of Love's Graphs

For some readers it will be a convenience to have this paper made self-contained by the inclusion of a brief explanation of Love's graphs.

With a given warp there is a limit to the number of picks that can be driven home by a loom; this determines loom weavability. The limit depends in part on the performance of a given loom, but mainly on the number of yarns and the diameters of the yarns, which variables determine what yarn can be fitted into the framework of warp and filling. "Cover Factors" include both diameter and number of yarns and make possible the preparation of relatively simple weavability graphs. One other variable must be provided for, and this is the ratio of the diameter of the filling yarn to the diameter of the warp yarn as expressed by count balance β. (Cover factors and count balance are defined later in the paper.) A difference in the diameters, *i.e.*, a difference between warp- and filling-yarn sizes, affects the geometrical relations.

If the yarns are regarded as flexible but incompressible cylinders and are given conventional diameters not too far from real diameters, then from purely geometrical considerations it is possible to compute conventional limits of weavability. These calculations, initiated by Peirce [3] for plain weave and carried through 5-harness weaves by Love, have resulted in Love's weavability graphs. These graphs represent geometrical weavability.

Love's graphs are laid out on arithmetic cross-section paper. If we examine the plain-weave graph (Figure 1)* as an illustration, we find that the warp cover factor K_1 is on the horizontal scale and the filling cover factor K_2 on the vertical scale. Separate curves are shown for count balance from 0.5 to 2.0. Any construction to the "southwest" of one of these lines is geometrically weavable, and any construction to the "northeast" is geometrically unweavable. In addition, the top and right-hand lines, $28K_2$ and $28K_1$, are also limits of weavability; 28 is the limit cover factor of plain weave for yarns side by side and touching.

On each graph the limiting curve is symmetrical when the same yarn is used for warp and filling, *i.e.*, $\beta = 1.00$. For count balance other than 1 the curves are not symmetrical.

To use the graph, first compute the warp and filling cover factors and the count balance in the cotton count system, the system on which Love's graphs are based. The two cover factors determine a point on the graph. If this point is to the "southwest" of the curve for the computed count balance the construction is geometrically weavable; if to the "northeast," it is geometrically unweavable.

Mathematics

It has been suggested that, for many practical users, it would be a convenience if no reference to other publications were required; hence in this paper no prior knowledge is assumed, even that of cover factors. One further explanation is given. It might be thought sufficient to write "do this and

* Figure numbers refer to the figures in Love's article in this issue.

do that and you come up with the answer," but experience has shown that this brevity leaves the human mind unsatisfied. The mind wants to understand, to know the "why." For this reason, the final equations are developed from fundamental principles. It is easier for those familiar with cloth geometry to skip than for those without such knowledge to look up scattered prior publications.

Love's graphs for limits of weavability are in terms of warp and filling cover factors and yarn balance. The numerical constants for computing diameters and hence cover factors and yarn balance depend upon the unit for measuring yarn size (which may be cotton count, denier, etc.) and upon the kind of fiber (a low-density fiber such as nylon makes a larger-diameter yarn than does a high-density fiber like viscose). Now Love's graphs were computed only for cotton count and cotton fiber. If the data at hand are for a different unit of yarn size and/or a different kind of fiber, then the figures must be converted to what they would be for cotton yarn measured in cotton count. The conversion of a different unit of yarn size into cotton count is well known. For handling the other problem—conversion from one kind of fiber to another—the writer has developed what he has termed the all-fiber system [1]. The essentials of this system and its application to the practical design of weavable fabrics follow.

Since cover factors and yarn balance are based on yarn diameters, we first consider this subject. A yarn is supposed to be a cylinder, and the size of a yarn cylinder is given in units of linear density (weight per unit length, for example, denier) or in reciprocal units (length per unit weight, for example, cotton count). The volume of a cylinder is length times cross-sectional area and, in homogeneous units, say centimeter, gram, cubic centimeter, and grams per cubic centimeter:

$$\begin{aligned}\text{volume} &= \text{length} \times \pi(\text{radius})^2 \\ &= \text{length} \times \pi(\text{diameter}/2)^2 \\ &= l\pi d^2/4.\end{aligned}$$

$$\text{weight of cylinder } W = \text{density} \times \text{volume} = \frac{Dl\pi d^2}{4}.$$

$$\text{linear density } H = W/l = D(\pi/4)d^2. \qquad (1)$$

$$\text{diameter } d = \sqrt{H}/\sqrt{\pi/4}\sqrt{D} \quad \text{(centimeter-gram units).}$$

We have now arrived at an equation which shows how the diameter of a cylinder (yarn) is related to its linear density (yarn size) and its volume density. The equation holds for any units, and if they are not homogeneous a diameter factor with symbol k_d appropriate to the units selected can be computed. We now write

$$\text{diameter } d = k_d\sqrt{H}/\sqrt{D},$$

and, if linear density is in reciprocal units N, then

$$\text{diameter } d = k_d/\sqrt{D}\sqrt{N}. \qquad (2)$$

When applied to yarns, the density is the bulk density of the yarn, D^y (not the fiber density).

To compute the diameter of a yarn of cotton count N we require the bulk density of the yarn. Peirce [3] assumed that all cotton yarns have a specific volume of 1.1 cc./g., or a bulk density of 0.909 g./cc. This value inserted in the equation in centimeter-gram units would give the value of the diameter in centimeters of a cotton yarn having a linear density of 1 g./cm. This is the diameter factor. However, for practical use we want the diameter factor in customary units: inch for diameter, reciprocal linear density in cotton count, and density in grams per cubic centimeter. If in the fundamental equation the centimeter-gram units of equation (1) are replaced by the desired units (for example, pounds $\times$ 453.6 = grams, and so on), Peirce's value of 0.909 is used for D, and the conversion factors are combined with $\pi/4$, the result is 0.0358, or

$$\text{(cotton: cotton count)} \quad \text{diameter } d \text{ (in.)} = \frac{0.0358}{\sqrt{N}} \qquad (2a)$$

The term in parentheses shows that the value is for cotton fiber and the yarn size is in cotton count, the numerical value depending upon both the kind of fiber and the unit of yarn size.

At this point we can compute the conventional diameter of cotton yarn of any cotton count. We now introduce another assumption which extends Peirce's assumption for cotton to other kinds of fibers; that is, we develop an all-fiber system.

The added assumption is that the bulk density of yarns made of different kinds of fibers is proportional to fiber density. A high-fiber-density fiber such as cotton (1.50 g./cc.) makes a higher-density yarn than nylon (1.14). An alternative statement

of the added assumption is that yarns are equally compact—under similar conditions fibers nest together to the same extent. Using D^y for bulk density of yarn, D^f for fiber density, subscript c to denote cotton, and subscript g for a given kind of fiber,

$$\frac{D_g^y \text{ (given fiber)}}{D_c^y \text{ (cotton)}} = \frac{D_g^f \text{ (density given fiber)}}{D_c^f \text{ (density cotton fiber)}};$$

$$D_g^y = \frac{D_c^y D_g^f}{D_c^f}. \tag{3}$$

Substituting for D in equation (2),

$$d = \frac{k_d}{\sqrt{D_g^y}\sqrt{N}} = \frac{\sqrt{D_c^f} k_d}{\sqrt{D_c^y}\sqrt{D_g^f}\sqrt{N}}. \tag{4}$$

As already stated, when Peirce's assumption of 0.909 is used for the bulk density of cotton yarn, the value of k_d is 0.0358, so that

$$d = \frac{\sqrt{D_c^f} \times 0.0358}{\sqrt{D_g^f}\sqrt{N}}. \tag{5}$$

Cotton fiber density $D_c^f = 1.50$, and $\sqrt{1.50} = 1.225$; when substituted in equation (5),

$$d = \frac{1.225 \times 0.0358}{\sqrt{D_g^f}\sqrt{N}} = \frac{0.0438}{\sqrt{D_g^f}\sqrt{N}}$$

$$= \frac{k_d^a}{\sqrt{D_g^f}\sqrt{N}}. \tag{6}$$

We have now arrived at an equation for the conventional diameter of a yarn of any cotton count made of any kind of fiber for which the fiber density is known. The value 0.0438 can therefore be recorded as the diameter factor, k_d^a, applying to all fibers. Note that the all-fiber value stems from the assumption adopted by Peirce for cotton yarn. The physical meaning of this all-fiber diameter factor is the diameter in inch units of a 1's cotton count yarn made of a hypothetical fiber of fiber density 1.

We are now prepared to develop cover factors following Peirce and the all-fiber system developed above. The width covered by parallel yarns depends upon the diameter of one yarn and the number of yarns. Suppose 28 cotton yarns of 1's cotton count lie side by side and touching, *i.e.*, compact parallel yarns: how many inches in width do they cover? The conventional diameter of a 1's cotton yarn is 0.0358 in. Therefore, the width covered is 28×0.0358, or 1.00 in., approximately.

The maximum number of 1's cotton yarns per inch of width is $1/k_d$, or 28. Fourteen cotton yarns of 1's cotton count cover $\frac{1}{2}$ in., and if equally spaced across 1 in., as in a warp, the relative cover would be 50%.

Substituting the value for the diameter (0.0358), the cover of cotton yarns per inch width is the number of yarns per inch times their diameter, or $n \times d$. Thus from (2a):

$$\text{cover} = n \times d = n \times 0.0358/\sqrt{N}. \tag{7}$$

In defining cover factor, Peirce simply omitted the value of the diameter factor:

$$\text{cotton cover factor } K = n/\sqrt{N}. \tag{8}$$

The omitted value provides the maximum conventional value of the cover factor (yarns side by side and touching). In this case the relative cover factor is 1.0; hence from (7),

$$1.0 = n \times 0.0358/\sqrt{N};$$

$$1.0 = K \times 0.0358. \tag{9}$$

For the cover factor to be that which provides complete cover,

$$\text{max. } K^* = 1/0.0358 = 28,$$

or, in general terms,

$$K^* = 1/k_d, \tag{10}$$

when k_d is the diameter factor for (given fiber: given unit of yarn size).

For developing cover factors in an all-fiber system, calculation of diameters must take fiber densities into account (from here on the symbol D, instead of D^f, denotes fiber density).

$$\text{(all-fiber: cotton count) } K^a = \frac{n}{\sqrt{D}\sqrt{N}} = \frac{K}{\sqrt{D}}, \tag{11}$$

and from equation (6)

$$\text{(all-fiber: cotton count) max. } K^{a*} = \frac{1}{k_d^a} = \frac{1}{0.0438} = 22.8, \tag{12}$$

and for

$$\text{(given fiber: cotton count) } K = \sqrt{D}K^a. \tag{13}$$

The last equation converts an all-fiber cover factor to the equivalent cover factor when the yarn is made of a fiber of fiber density D. For example, when the maximum all-fiber cover factor of 22.8 is

converted to cotton by multiplying by $\sqrt{D_c} = 1.225$, the value 28 is reproduced.

At this point we have arrived at a method of converting cover factors for one kind of fiber into the equivalent cover factor for any other kind of fiber, the two fiber densities being known.

The yarn balance (Love's count balance) is the ratio of the filling yarn diameter to the warp yarn diameter. For cotton yarns, subscript w denoting warp and f filling:

$$\beta = \frac{d_f}{d_w} = \frac{0.0358/\sqrt{N_f}}{0.0358/\sqrt{N_w}} = \frac{\sqrt{N_w}}{\sqrt{N_f}}, \qquad (14)$$

which is the formula used by Peirce and Love. If the fiber is other than cotton,

$$\beta = \frac{d_f}{d_w} = \frac{0.0438/\sqrt{D_f}\sqrt{N_f}}{0.0438/\sqrt{D_w}\sqrt{N_w}} = \frac{\sqrt{D_w}\sqrt{N_w}}{\sqrt{D_f}\sqrt{N_f}}. \qquad (15)$$

If, as is the usual case, the same kind of fiber is used in both warp and filling, then fiber densities cancel along with the diameter factors. If warp and filling fibers are different, then the all-fiber formula is used.

We are now equipped for conversion of any raw data into cover factors and yarn balance as they appear on Love's weavability graphs. Two numerical examples of the computations for staple-yarn fabrics are given below, followed by data which compare actual weaving experience for various fibers and weaves with the theoretical taken from the graphs. The steps in the comparison are as follows: The warp and filling cover factors and yarn balance in the (cotton: cotton count) system are computed for the fabric known to be at the limit of weavability. The filling cover factor at the intersection of the warp cover factor and yarn balance is read off the graph. Finally, the difference in filling cover factors, loom minus graph, is computed; a plus difference shows that the loom does better than the graph, and a minus difference that it falls short of the graph.

An example of computations for fabrics constructed of filament yarns is given in the section Filament-Yarn Fabrics.

Staple-Yarn Fabrics

Plain-Weave Cotton Fabric: Numerical Example

Is a plain-weave cotton fabric weavable when the construction is 29.0 ends of 11.7s/11 cotton count and 19.0 picks of 10.8s/6?

warp-yarn cotton count $N_w = 11.7\text{s}/11$,
equivalent 1.064; $\sqrt{1.064} = 1.032$,

filling-yarn cotton count $N_f = 10.8\text{s}/6$,
equivalent 1.800; $\sqrt{1.800} = 1.342$.

ends per inch $n_w = 29.0$,
picks per inch $n_f = 19.0$.

(cotton: cotton count) warp cover factor K_w
$= n_w/\sqrt{N_w} = 29.0/1.032 = 28.1$,

(cotton: cotton count) filling cover factor K_f
$= n_f/\sqrt{N_f} = 19.0/1.342 = 14.2$.

yarn balance $\beta = \sqrt{N_w}/\sqrt{N_f} = 1.032/1.342 = 0.77$.

From Love's graph (Figure 1), $K_f = 12.3$, which is the maximum filling cover factor weavable on a 28.1 cover-factor warp, the given K_f minus the geometrically (graph) calculated max. $K_f = 14.2 - 12.3 = +1.9$.

This excess in filling cover factor (over the theoretical maximum) can be woven if a heavy enough loom is selected for the job.

Twill Weave Worsted Fabric: Numerical Example

A worsted 2/2 twill is designed of 72 ends of 2-ply worsted yarns of equivalent 9.6 worsted count and 46 picks of the same yarn; is it weavable? The fiber density D of wool is 1.305 g./cc.; $\sqrt{1.305} = 1.142$, and the fiber density of cotton is 1.50; $\sqrt{1.50} = 1.225$.

First step.—Convert worsted to cotton count (8.40-yd. cotton hank ÷ 5.60-yd. worsted hank = 1.50).

(cotton count, warp) N_w = worsted count/1.50
$= 9.6/1.50 = 6.40$,
(cotton count, filling) $N_f = 9.6/1.50 = 6.40$.

(square root cotton count, warp) $\sqrt{N_w}$
$= \sqrt{6.40} = 2.530$,
(square root cotton count, filling) $\sqrt{N_f}$
$= \sqrt{6.40} = 2.530$.

yarn balance $\beta = \sqrt{N_w}/\sqrt{N_f} = 2.530/2.530 = 1.00$.

Second step.—Compute (wool: cotton count) cover factors.

(cover factor, warp) $K_w = n_w/\sqrt{N_w}$
$= 72/2.530 = 28.46$,

(cover factor, filling) $K_f = n_f/\sqrt{N_f}$
$= 46/2.530 = 18.18.$

Third step.—Compute (all-fiber: cotton count) cover factors (go into all-fiber system).

(all-fiber cover factor, warp) $K_w^a = K_w/\sqrt{D}$
$= 28.46/1.142 = 24.92,$

(all-fiber cover factor, filling) $K_f^a = K_f/\sqrt{D}$
$= 18.18/1.142 = 15.92.$

Fourth step.—Compute (cotton: cotton count) cover factors (go from all-fiber to cover factors on graph).

(cotton: cotton count) K_w
$= \sqrt{D}K_w^a = 1.225 \times 24.92 = 30.5,$

(cotton: cotton count) K_f
$= \sqrt{D}K_f^a = 1.225 \times 15.92 = 19.5.$

Entering Love's graph for 4-harness weave (Figure 4) at $\beta = 1.00$ and warp cover factor 30.6, the maximum weavable filling cover factor is 20.2. Required-of-loom K_f 19.5 minus graph 20.2 equals -0.7. The design should be weavable. (This example is item 2 in Table IV.)

It is evident that, once the size is expressed in cotton count, steps 2, 3, and 4 can readily be combined in one operation:

(cotton: cotton count) K
$= (\sqrt{D}\,\text{cotton}/\sqrt{D}\,\text{given})(n/\sqrt{N}).$

When a mill is regularly handling some fiber other than cotton in a unit of yarn size other than cotton count, it is a convenience to employ a conversion factor for converting (given fiber: given count) cover factor into (cotton: cotton count) cover factor. The mathematics for calculating such a conversion factor will be illustrated by the warp of this numerical example.

$$\text{(all-fiber: cotton count) } K^a = \frac{n}{\sqrt{D}\sqrt{N}}, \qquad (11)$$

$$\text{(cotton: cotton count) } K = \frac{\sqrt{D}\,\text{cotton}\; n}{\sqrt{D}\sqrt{N}}.$$

Next substitute the value 1.225 for the square root of cotton-fiber density and 1.142 for the square root of wool-fiber density; substitute for cotton count its value in worsted count.

(cotton: cotton count) K

$$= \frac{1.225n}{1.142\sqrt{\text{worsted count}/1.50}}$$

$$= \frac{1.225\sqrt{1.50}n}{1.142\sqrt{\text{worsted count}}}$$

$= 1.31 \times K$ (wool: worsted count)

For the warp of 72 ends of 9.6 worsted count,

$$\text{(wool: worsted count) } K_w = \frac{72}{\sqrt{9.6}} = \frac{72}{3.10} = 23.2,$$

(cotton: cotton count) $K_w = 1.31 \times 23.2 = 30.5.$

This value is the same as that computed by the step-by-step method.

Comparison of Calculated Values with Actual Loom Data for Staple-Yarn Fabrics

1. Plain-weave fabrics.—Table I shows data from United States Rubber Company on plain-weave cotton ducks woven of ply yarns on heavy duck looms to the commercial limit of picks. The belt ducks are warp heavy, hose ducks are approximately square, and one experimental duck is filling heavy. One Dynel and one staple Orlon duck are included. The comparison of these loom-state data with corresponding figures from the graphs, expressed in terms of (cotton: cotton count) cover factors, is given in Table I. To provide an idea of the range of ducks covered, a column for fabric weight has been added.

TABLE I. LOOM LIMIT OF WEAVABILITY OF PLAIN-WEAVE PLY-YARN DUCKS

Weight (oz./sq. yd.)	Yarn balance (β)	Loom cover factors: warp (K_w)	Loom cover factors: filling (K_f)	Graph filling limit (K_f)	Loom minus graph
28.9	0.86	27.2	14.6	13.0	+1.6
29.0	0.91	30.3	13.3	13.1	+0.2
30.1	0.81	27.8	14.2	13.0	+1.2
30.9	0.94	26.8	15.6	13.6	+2.0
31.7	0.79	30.4	12.3	12.0	+0.3
36.0	0.83	26.4	13.7	12.8	+0.8
16.8	1.00	14.9	18.4	18.2	+0.2
18.6	1.01	15.6	16.5	16.8	−0.3
20.6	1.16	19.4	17.5	15.5	+2.0
29.9	1.00	17.7	17.7	15.1	+2.6
26.3	1.08	14.6	20.0	18.3	+1.7
17.4*	0.99	16.8	17.3	15.6	+1.7
12.2†	1.02	22.1	15.2	14.4	+0.8

* Dynel. † Staple Orlon. Others are cotton.

There is a geometrical upper limit of 28 to either the warp or the filling cover factor; the United States Rubber Company's duck mill regularly weaves warp cover factors higher than this limit; one as high as 30.4 is to be noted above.

As shown in Table I, the loom has done better than the graph in every instance but one. In practical design, say to meet a duck specification for filling strength commercially best supplied by maximum picks, United States Rubber Company takes advantage of the capabilities of its heavy duck looms. Before designing beyond the limits of the graph, however, it is important to "know your loom."

It should be noted that, although some of the figures were based on experiments definitely to drive home the maximum picks, others are taken from existing indications that approximately the maximum picks have been reached.

The Orlon fabric included in Table I affords an illustration of the advantage of the all-fiber system. Here the fiber density is 1.14 as compared with 1.50 for cotton. Had the difference in fiber densities not been taken into account, K_w would have been computed as 19.2, K_f as 13.3, K_f on the graph would have read 14.9, and loom-minus-graph would be -1.6 instead of $+0.8$.

Constructions listed in *Clark's Weave Room Calculations* provide data for computing cover factors of cotton heavy naught ducks and hard texture sail ducks, both types of plain weave woven of ply yarns. Listed by Clark are 16 naught ducks, with weights ranging fron 34 to 52 oz./sq. yd.; all exceed the graph limit of weavability. Further listed are 32 sail ducks, all but 6 of which exceed the graph, with small minus figures for the 6 exceptions. These are commercial ducks, and falling short of the graph does not mean that tighter duck could not have been woven. The 32 sail ducks range from 11.5 to 32.7 oz./sq. yd., and the yarns range from 2 to 7 ply.

This evidence, added to that of our own data, gives assurance that heavy duck looms weaving ply staple yarns can normally be depended upon to outperform the graph.

2. Oxford-weave fabrics.—The Southern Regional Research Laboratory [2] reports the maximum picks which can be inserted with and without the SRL loom attachment for overpickage. Data from this report, together with additional information given in personal communication, are utilized for the comparison in Table II. The cotton fabrics were woven of ply yarns, with the exception of the warp of the last oxford and the twill, in which the warp is singles. The 3/1 twill is included with the oxford weaves. Only the results without the attachment are shown.

3. Twills, cotton.—Snowden [4] has published data on the loom limits of weavability of approximately square cotton fabrics. The warp and filling yarns were 10.6s/1 cotton count for both warp and filling. The last points on Figure 5 of Snowden's paper, the limits of weavability, have been used for computing Table III. The graph limits for 3/3 and higher twills are not covered by Love's graphs, and these have been estimated by extrapolation of a plot of figures taken from his graphs. The loom is consistently lower than the graph, and by approximately the same differences.

4. Twills, worsted.—Snowden, in the same paper [4], reports the weavability of 2/2 twills woven of 2-ply worsted yarn, where both warp and filling yarns are the equivalent of 9.6s worsted count. The yarn balance is 1.00. The setting of the loom was kept at a weight-lever oscillation of 8°.

The agreement is good up to 48 ends per inch. The results may suggest that the nature of looms is such that it is easier to produce high warp than high filling cover factors. However, the loom setting

TABLE II. WEAVABILITY OF COTTON OXFORDS

Weave	Yarn balance (β)	Loom cover factors: warp (K_w)	Loom cover factors: filling (K_f)	Graph filling limit (K_f)	Loom minus graph
Oxford	1.24	30.1	16.9	15.8	+1.1
Oxford	1.00	32.0	14.5	14.0	+0.5
Oxford	1.41	29.2	17.3	16.5	+0.8
Oxford	0.78	28.3	11.6	12.6	−1.0
Oxford	1.66	27.3	16.1	17.6	−0.7
3/1 Twill	1.66	27.3	17.7	23.5	−5.8

TABLE III. WEAVABILITY OF COTTON TWILLS

Twill	Loom: Yarns per inch ($n_w = n_f$)	Loom: Cover factors ($K_w = K_f$)	Graph limit ($K_w = K_f$)	Loom minus graph
2/1	55	16.9	19.7	−2.8
2/2	61	18.7	22.2	−3.5
3/3	78	24.0	26.4	−2.4
4/4	88	27.0	30.1	−3.1
5/5	100	30.7	33.2	−2.5
6/6	112	34.4	36.0	−1.6

TABLE IV. WEAVABILITY OF 2/2 WORSTED TWILLS

Ends per inch (n_w)	Loom cover factor: warp (K_w)	Loom cover factor: filling (K_f)	Graph filling limit (K_f)	Loom minus graph
80	33.8*	19.0	20.0	−1.0
72	30.4	19.4	20.2	−0.8
64	27.0	20.3	20.4	−0.1
56	23.6	21.5	21.5	0.0
48	20.3	22.4	29.0	−6.6
40	16.9	23.6	31.4	−7.8
32	13.5	24.5	31.4	−6.9

* Over Love's limit of 31.4 for either warp or filling.

was kept constant, and it is possible that readjustment would have permitted driving home more picks in the low ends part of the table. It is to be noted that with plain weave it was possible, when a deliberate attempt was made, to weave a filling-heavy cotton duck to exceed the graph.

5. Miscellaneous weaves.—The Textile and Leather Laboratories of Quartermaster Research and Development Division have unpublished figures on weavability which have been made available for inclusion in this paper. The fabrics were woven of cotton singles, warp and filling, with the exception of the last two sateens, which were woven with cotton/nylon blended filling yarns. The (cotton: cotton count) filling cover factors of the blends were computed using the all-fiber system.

Filament-Yarn Fabrics

This paper would be incomplete without data on filament-yarn fabrics, since those weaving such fabrics will naturally be interested in knowing how closely the graphs agree with practical mill experience. The Wellington Sears Company have generously made available their data in this field.

TABLE V. MISCELLANEOUS WEAVES

Weave	Yarn balance (β)	Loom cover factors: warp (K_w)	Loom cover factors: filling (K_f)	Graph filling limit (K_f)	Loom minus graph
Plain	1.15	22.8	16.3	15.1	+1.2
Oxford	1.15	23.7	16.7	15.7	+1.0
HB* twill	1.15	22.9	20.0	22.0	−2.0
Mod. HB† twill	1.15	23.0	19.6	21.9	−2.3
Sateen	1.15	23.5	22.3	24.4	−2.1
Sateen‡	1.13	23.6	21.2	24.3	−3.1
Sateen§	1.12	23.5	20.5	24.5	−4.0

* Herringbone twill.
† Modified herringbone twill.
‡ Filling yarn, cotton 75/nylon 25.
§ Filling yarn, cotton 50/nylon 50.

Equations for handling the filament-yarn data will first be presented. The symbol H is used for yarn size in direct units of linear density and N for reciprocal units; it will be noted that where H appears in the numerator of an equation N appears in the denominator, and conversely.

(given fiber: denier) cover factor K
$$= (\text{yarns per inch}) \times \sqrt{\text{yarn denier}} = n\sqrt{H}.$$
$$\text{yarn balance } R_r = \sqrt{H_f}/\sqrt{H_w}.$$

(all-fiber: denier) cover factor K^a
$$= K/\sqrt{\text{fiber density, g./cc.}} = K/\sqrt{D}.$$

(given fiber: cotton count) cover factor K
$$= 0.0137K \text{ (given fiber: denier)}$$

(cotton: cotton count)
$$= \frac{\sqrt{D_c}}{\sqrt{D_g}} \times 0.0137K \text{ (given fiber: denier)} \qquad (16)$$
$$= \frac{1.225}{\sqrt{D_g}} \times 0.0137K \text{ (given fiber: denier).}$$

(cotton: cotton count) cover factor K
$$= 0.0168K^a \text{ (all-fiber: denier).}$$

In United States Rubber Company handling of filament-yarn fabric data, cover factors are regularly computed in (all-fiber: denier). For the following tables, therefore, it has been necessary only to copy off (all-fiber: denier) figures, and, setting up the constant 0.0168 as a multiplier, go down the columns of (all-fiber: denier) cover factors to compute the (cotton: cotton count) cover factors which appear in the graphs.

Plain-Weave Nylon Filament-Yarn Fabric: Numerical Example

This example involves conversion of units and the use of the all-fiber system. Is a plain-weave nylon filament-yarn fabric weavable when constructed of 58 ends of 260 den./2 and 40 picks of 260 den./2? Fiber density of nylon is 1.14; $\sqrt{1.14} = 1.068$; fiber density of cotton = 1.50; $\sqrt{1.50} = 1.225$. We conclude from the computations on page 1091 that the construction should be wearable.

The warp in the computations will be used as an example of conversion of (nylon: denier) cover factor to (cotton: cotton count), using the conversion factor 0.0157 derived from equation (16) by substituting for D_g the value for nylon, 1.14.

COMPUTATIONS FOR NUMERICAL EXAMPLE

	Warp	Filling
First step. Convert denier to cotton count		
Yarn size, denier units (H)	260 den./2 = 520	260 den./2 = 520
Yarn size, cotton count ($N = 5315/H$)	10.22	10.22
Square root ($\sqrt{N}$)	3.197	3.197
Yarn balance ($\beta = \sqrt{N_w}/\sqrt{N_f}$)	1.00	
Second step. Compute (nylon : cotton count) cover factors		
Yarns per inch (n)	58	40
(Nylon : cotton count) cover factor ($K = n/\sqrt{N}$)	18.14	12.51
Third step. Go into all-fiber system		
(All-fiber : cotton count) cover factor ($K^a = K/\sqrt{D \text{ nylon}}$)	16.99	11.71
Fourth step. From all-fiber go to (cotton : cotton count) appearing on graphs		
(Cotton : cotton count) cover factor ($K = \sqrt{D \text{ cotton}}\ K^a$)	20.8	14.3
Graph max. weave filling cover factor $K_f = 14.5$.		
Required-of-loom K_f minus graph $K_f = 14.3 - 14.5 = -0.2$.		

(nylon : denier) $K_w = n_w\sqrt{H_w} = 58\sqrt{520}$
$= 58 \times 22.8 = 1322.$

(cotton : cotton count) $K_w = 0.0157 \times 1322$
$= 20.8.$ (checks)

The Wellington Sears Company data on weavability of filament viscose and filament nylon fabrics are presented in Tables VI and VII for comparison with the graphs. In considering these figures a number of things are to be kept in mind. The Wellington Sears Company wishes it emphasized that the fabrics listed as at the limit of weavability were not in every instance woven specifically with a view to determining the maximum number of picks possible, and, further, that not all fabrics were woven on the same model of loom. The cover factors were computed on the filament-yarn manufacturer's nominal yarn denier. To the extent that additional twist was added at the mill before weaving, the actual yarn denier is greater than the nominal.

TABLE VI. WEAVABILITY OF VISCOSE FILAMENT-YARN FABRICS *

Weight (oz./sq. yd.)	Yarn balance (β)	Loom cover factors: warp (K_w)	Loom cover factors: filling (K_f)	Graph filling limit (K_f)	Loom minus graph
		Plain Weave			
11.5	1.00	15.4	14.5	17.2	−2.7
22.5	0.816	25.1	12.2	12.9	−0.8
23.5	0.816	25.1	12.2	12.9	−0.8
27.4	0.816	18.8	13.6	13.9	−0.3
		Oxford Weave			
6.9	1.41	20.3	13.4	18.1	−4.7

* Wellington Sears Company data.

Wellington Sears Company also provided data on spun nylon fabrics approximately at the limits of weavability. Fabric weights ranged from 10 to 17 oz./sq. yd. Only the loom-minus-graph figures follow: plain weave, +2.6, +1.9, +2.9, and 2/2 twill, −4.2.

General Remarks

Whether or not a loom can reach or exceed geometrical limits obviously depends upon the loom and loom conditions. A loom not designed for weaving tightly woven fabrics, and particularly a light loom weaving a heavier fabric than it was designed for, will probably not reach the limits of the graph. Running conditions include width of fabric and rate of weaving, among other variables. The high-pickage attachment developed by the

TABLE VII. WEAVABILITY OF NYLON FILAMENT-YARN FABRICS *

Weight (oz./sq. yd.)	Yarn balance (β)	Loom cover factors: warp (K_w)	Loom cover factors: filling (K_f)	Graph filling limit (K_f)	Loom minus graph
		Plain Weave			
2.5	1.41	17.8	11.2	16.8	−5.7
5.0	1.41	14.1	16.8	18.2	−1.4
5.8	1.00	18.7	12.9	14.8	−1.9
6.0	1.00	18.1	13.6	15.0	−1.5
6.1	1.00	18.1	14.2	15.0	−0.8
6.4	1.00	19.4	13.6	14.7	−1.2
7.1	1.00	19.4	14.4	14.7	−0.3
7.7	1.00	20.8	14.3	14.5	−0.2
8.8	1.23	24.5	15.0	15.4	−0.4
10.5	0.94	17.4	16.3	15.2	+1.1
12.0	1.23	25.1	15.7	15.4	+0.3
14.5	1.00	16.9	16.9	15.6	+1.3
		Oxford Weave			
19.0	1.00	30.3	13.0	14.1	−1.1
		2/1 Twill Weave			
17.5	1.826	22.9	24.1	21.7	+2.4
		2/2 Twill Weave			
13.3	1.225	24.6	20.7	22.0	−1.3

* Wellington Sears Company data.

Southern Regional Research Laboratory [2] is an extreme example of manipulation of the loom to increase the number of picks. There is some indication that the limits in weaving singles yarn may be lower than for ply.

We turn next to a comparison of the conventions underlying the geometry, briefly summarized in the introduction, with the actual properties of yarns.

The bulk density assumed by Peirce [3] for all cotton yarns leads to the equation

$$\text{yarn diameter (in.)} = (\text{yarn diameter factor})/\sqrt{\text{cotton count}} = k_d/\sqrt{N} = 0.0358/\sqrt{N} \quad \text{(Peirce's assumption)}.$$

Actual diameter factors computed from diameter measurements on yarns do not agree with Peirce's assumption; illustrative figures are given by the author in [1]. The all-fiber system was introduced by the author to extend the handling of yarn diameters to fibers other than cotton by the simple expedient of taking fiber density into account.

Another assumption is that the yarns are incompressible cylinders. They are in fact compressible, and the flattening at intersections is shown on most published photographs of cross sections of woven fabrics. It is possible to compute the effective "diameter" (more precisely, the thickness) of yarns as they lie in the fabric by the use of approximation formulas developed by Peirce. Computations have been made for ply yarns as they lie in some of United States Rubber Company cotton ducks, and the effective diameter (thickness) factors averaged 0.0270 for 11 belt ducks and 0.0214 for 6 hose ducks; belt ducks are warp heavy and hose ducks are approximately square. Both averages are substantially lower than Peirce's assumption. United States Rubber Company laboratory has also measured thickness under increasing pressure (compressibility) of cotton singles and ply yarns.

The reader should not be deterred by all these ifs, ands, and buts. The practical question is whether or not yarns behave in fabrics as though they had the bulk density assumed by Peirce for cotton, and the extension to other fibers by the all-fiber system. Most yarns are bulkier than assumed, but in crowding together in fabrics, especially in the tight weaves under consideration, they tend to compress to a higher density more nearly that assumed by Peirce. The comparison of loom with geometrically calculated weavability is the real test.

Summary

The foregoing comparison covers both staple-yarn and filament-yarn fabrics, different kinds of fiber, all the weaves for which Love has provided graphs, and a wide range of other textile variables. Considering the nature of the data and the assumptions on which the geometry is based, the agreement between loom performance and the predictions of the graphs is surprisingly close. If a proposed design is substantially within the weavable area of a graph, it may confidently be expected to be weavable and if substantially outside this area to be unweavable. There is a zone of uncertainty which is narrowed as experience with a given model of loom and type of fabric accumulates, that is, when the designer "knows his loom."

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gent comments. Wellington Sears Company generously made available data on the weavability of filament-yarn fabrics without which this article would have been less complete. Quartermaster Research and Development Division approved publication of figures on miscellaneous weaves. Sincere appreciation goes to Louis Love, who made his weavability graphs available to the author in advance of publication and thereby made it possible for this paper to appear simultaneously with the publication of his graphs.

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(Revised manuscript received September 17, 1954.)

Weavability Graphs

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With limited issuance of preprints of Mr. Love's article, a demand arose for enlargements of the maximum weavability charts. In one large company numerous sets were distributed among its various division and personnel. To meet such requirements of practical technologists and designers, Graphs 1 and 2 to 7 will be made available in size 11 by 17 inches. Each set will be accompanied by reprints of both Love and Dickson articles.

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Book Reviews

Advances in Carbohydrate Chemistry, Vol. VII. Edited by C. S. Hudson, M. L. Wolfrom, and S. M. Cantor. New York, Academic Press, Inc., 1952. ix + 370 pages. Price, $7.50.

(Reviewed by Eugene Pacsu, Princeton University, Princeton, N. J.)

This new addition to the *Advances* marks the return of Professor M. L. Wolfrom to the editorial staff of this much-needed series of review articles in the field of carbohydrate chemistry. In the present volume one German, two American, and eight British scientists present in eight authoritative chapters selected topics with up-to-date literature references. The volume contents are as follows:

"The Methyl Ethers of the Aldopentoses and of Rhamnose and Fucose," by R. A. Laidlaw and (the late) E. G. V. Percival (83 references); "1,6-Anhydrohexofuranoses, a New Class of Hexosans," by R. J. Dimler (36 references); "Fructose and Its Derivatives," by C. P. Barry and J. Honeyman (215 references); "Psicose, Sorbose, and Tagatose," by J. V. Karabinose (175 references); "Acetals and Ketals of the Tetritols, Pentitols and Hexitols," by S. A. Barker and E. J. Bourne (172 references); "The Chemistry of the 2-Amino Sugars (2-Amino-2-Deoxy-Sugars)," by A. B. Foster and M. Stacey (136 references); and "The Size and Shape of Some Polysaccharide Molecules," by C. T. Greenwood (130 references).

The articles are uniformly well written in concise and clear style, and careful editorial work has practically freed the text of typographical errors.

Advances in Carbohydrate Chemistry, Vol. VIII. Edited by C. S. Hudson and M. L. Wolfrom. New York, Academic Press, Inc., 1953. xvii + 408 pages. Price, $10.00.

(Reviewed by Eugene Pacsu, Princeton University, Princeton, N. J.)

The latest volume of the *Advances* appeared under the editorship of C. S. Hudson and M. L. Wolfrom. The sudden death of Dr. Hudson on December 27, 1952, deprives this indispensable reference work of one of its founders and its guiding spirit ever since its inception in 1944. An obituary of Sir James Irvine, written by Professor E. L. Hirst for this volume, portrays another great pioneer and inspiring leader whom carbohydrate chemistry lost in 1952.

The text of the new volume contains expert contributions by eleven authors, one Japanese, four British, and six American, who in nine comprehensive articles present the following topics, all of which are of great interest to those who wish to obtain a full picture on the present state of knowledge with regard to the particular subjects:

"Relative Reactivities of Hydroxyl Groups of Carbohydrates," by James M. Sugihara (182 references); "The Chemistry of the 2-Desoxysugars," by W. G. Overend and M. Stacey (248 references); "Sulfonic Esters of Carbohydrates," by R. Stuart Tipson (429 references); "The Methyl Ethers of D-Mannose," by G. O. Aspinall (59 references); "The Chemical Synthesis of D-Glucuronic Acid," by C. L. Mehltretter (83 references); "D-Glucuronic Acid in Metabolism," by H. G. Bray (165 references); "The Substituted-Sucrose Structure of Melezitose," by Edward J. Hehre (37 references); "Composition of Cane Juice and Cane Final Molasses," by W. W. Binkley and M. L. Wolfrom (135 references); and "Seaweed Polysaccharides," by T. Mori (151 references).

The carefully compiled author index (19 pages) and subject index (33 pages) greatly facilitate locating of desired references.

The Reactivity of Free Radicals. A General Discussion of the Faraday Society. Aberdeen, Scotland, The Aberdeen University Press, Ltd., 1953. 256 pages. Price, 35/.

(Reviewed by Dean Henry Eyring, University of Utah, Salt Lake City)

The Faraday Society held general discussions in 1934 and 1947 and again in 1952 on free radicals. The last conference is reported in this book.

The beginning three papers by Herzberg and Ramsay, by Norrish, and by Porter and Wright give an interesting account of high concentration of free

radicals secured by flash photolysis and measured and followed by absorption spectra. This permits the measurement of a variety of reactants. Lossing, Ingold, and Tickner report on the use of the mass spectrometer to follow the decomposition of dimethyl ether and other similar compounds. Next follow Majury and Steacie's work on reaction of methyl radicals with the hydrogen isotopes and Berlie and LeRoy's report on the reaction of atomic hydrogen with ethane. Then follow eight other papers on gas-phase reactions.

After a general discussion of these papers the second half of the symposium dealing with reactions in the liquid phase is given. This consists of eleven interesting papers followed again by a general discussion.

This is an excellent symposium, well reported, which must be read by people interested in free radicals.

Fibre Science, Second Edition. Edited by J. M. Preston. Manchester, England, The Textile Institute, 1953. xix + 421 pages. Price, $6.00.

(Reviewed by E. R. Kaswell, Fabric Research Laboratories, Inc., Boston, Mass.)

The first edition of this excellent book, published by the British Textile Institute, appeared in 1949. The second edition, revised and enlarged, was released in 1953. The book is composed, essentially, of eighteen post-advanced lectures delivered at the College of Technology, Manchester, January through July, 1947. The seventeen chapters are contributed by fifteen outstanding physicists and chemists.

As might be expected, this second edition has permitted the correction of many of the typographical errors, ambiguities, and other minor defects which inevitably appear in any first edition. As an example, headings and subheadings are more clearly marked, and this makes for the easier finding of desired subject matter.

Much of the content has been brought up to date by inclusion of additional information published in the four-year interim between editions. Thus, the new edition is about one-fourth larger than the old. As Dr. Preston points out in his preface, since different topics have advanced to different extents, some chapters have been altered more than others. Thus, chapters 2, 4, 7, 8, 9, 10, and 13 have had minor or no changes. Chapters 1, 3, 6, 11, 12, 15, 16, and 17 have had moderate changes, while Chapters 5 on protein fibers and 14 on plant cell wall in relation to fiber structure have been altered somewhat more extensively.

The book thoroughly covers the basic physics, chemistry, and technology of fibers and of polymers capable of being formed into fibers. Included are such topics as macromolecular structure, molecular weight, wave-mechanical considerations, x-ray properties, crystalline and amorphous regions, optical properties, and the chemistry of cellulose, amylose, chitin, pectic acid, alginic acid, proteins, keratin, and other synthetic fiber-forming polymers.

Especial care has been taken to add those polymers which have become commercially important or promising within the past five years. For example, additional information is given on the polyamides, polyesters, polytriazoles, polyacrylonitrile, and polystyrene.

A welcome addition is the author index, together with an improved subject index and expanded bibliography. These are extremely useful in any book intended for reference use.

In summary, this second edition of *Fibre Science* is a creditable improvement over the first edition of a book already proved to be of outstanding caliber and value.

Soap Manufacture, Vol. I: **Fats.** J. Davidsohn, E. J. Better, and A. Davidsohn. New York, Interscience Publishers, Inc., 1953. 525 pages. Price, $12.50.

(Reviewed by Frank W. Volz and Dr. L. Safrin, J. Eavenson Soap Co., Camden, N. J.)

This book, which is the first of two volumes, consists of four parts dealing with the theoretical principles of soap manufacture, raw materials, practical soap-boiling processes, and special soap products. The senior author is well known in Europe as an expert on oils, fats, and soaps, and has previously published a number of books and articles on this subject.

The early chapters on the theoretical aspects of saponification, structure, and phase behavior will be difficult for a person not well grounded in the fundamentals of physical and colloidal chemistry, since the authors try to condense this difficult and still controversial material into a relatively few pages. How-

ever, the presentation of Merklen's practical conceptions of the phase rule is excellent, particularly since the parts dealing with the threshold lye concentration are of importance for a soap maker dealing with a wide variety of raw materials. The applications of the "66% rule" to the study of soap-boiling systems are suitable guides for special problems. It would seem better if, in future editions, the theoretical section of the book were expanded and published as a separate volume.

The chapters on the distribution of glycerine and the decrease of acid value of neat soap and nigre will be very helpful to the practical soap manufacturer. We welcome the material on organic builders which is brought up to date by including the ethylene diamines, fluorescent dyes, and CMC.

The most important chapters deal with soap boiling and special soaps. This section contains an exhaustive list of methods, with a detailed description of each, as well as of the problems involved. Some of these techniques are more suitable for continental European practice and are either obsolete or of no importance in the United States. They might be appreciated in the Latin American countries.

We think this book is valuable enough to find its place in the library of every soap maker, since it is an excellent manual and seems to be one of the most complete on the subject. We think, however, that a beginner will have to turn first to the older American literature, especially to the books of Thomssen. We eagerly await the appearance of Volume II, which will deal with equipment, design, glycerine recovery, and analytical control.

New Fibres from Proteins. R. L. Wormell. New York, Academic Press, Inc., 1954. xx + 208 pages. Price, $5.80.

(Reviewed by Alfred E. Brown, Harris Research Laboratories, Inc., Washington, D. C.)

Dr. Wormell has had many years of experience at Courtaulds, Ltd., working on protein fibers, and has written this first book devoted entirely to this subject. One of the author's objects is to record an accumulation of facts, experiments, and observations on regenerated protein fibers. Although the book is by no means an exhaustive treatise into every aspect on protein fibers, it does indeed include many facts which should be of great value to workers in the field. The general discussion on protein raw materials in the early chapters, the specific discussions on the preparation of spin dopes (Chapter 5), their use for extrusion into fibers (Chapter 6), and their aftertreatment to insolubilize the filaments (Chapter 7), along with extensive literature and patent references, are most useful. Chapter 8, which discusses all types of cross-linking treatments, is well done, although some of the proposed reactions of formaldehyde with proteins on pages 93 and 98 are open to question.

The second object of the book is to present a "corpuscular theory" offered to "remove some confusion of thought on the behavior of protein fibers." This concept involves a linked series of corpuscles in the form of protein fibers. It is expounded at some length in individual chapters, and indeed permeates much of the book as an explanation of protein-fiber behavior. Although the idea is an interesting one, in the reviewer's opinion, many of the phenomena explained by it are much better explained by the currently accepted theories of protein structure and denaturation. In a sense, this corpuscular concept dilutes the factual matter, especially compilations of data, presented in the book, but this should not interfere with its value to research workers in this ever-expanding textile field.

The Physical Chemistry of Dyeing and Tanning. Discussions of the Faraday Society No. 16. Aberdeen, Scotland, The Aberdeen University Press, Ltd., 1954. 226 pages. Price, 35/.

(Reviewed by Dr. Fred Fordemwalt, American Cyanamid Co., Bound Brook, N. J.)

This book provides in a single volume the twenty-two separate papers presented at a General Discussion of the Physical Chemistry of Dyeing and Tanning held by the Faraday Society at the University of Leeds in September, 1953. As suggested in the introduction, ". . . the range of the Discussion is truly enormous."

The papers are presented in full, with figures, tables, and literature references. The introduction of each paper by a condensed abstract is quite helpful to the reader. Another interesting feature is the presentation of the general discussions relating to the subjects discussed at the meetings.

The twenty-two papers can be roughly grouped in subject matter as follows: two deal with cellu-

losics, three with synthetics, seven with general dye properties or problems, four with wool or hair, and six with subjects directly related to tanning. As one would judge from the title, the presentations are for the most part theoretical. This book will be a valuable source of materials for all researchers in those fields and for others who are concerned with the more fundamental factors involved in dyeing and tanning processes. It is a valuable addition to the growing list of General Discussions of the Society.

Matthews' Textile Fibers; Their Physical, Microscopic, and Chemical Properties, Sixth Edition. Edited by Herbert R. Mauersberger. New York, John Wiley & Sons, Inc., 1954. 1283 pages. Price, $16.50.

Matthews' Textile Fibers, which has been a classic reference work ever since its first appearance in 1904, is now in its sixth edition, revised and brought as nearly up to date as is possible in view of the constant flow of new developments both with respect to man-made fibers and to chemical alterations of properties of cotton and wool.

Professor J. Merritt Matthews wrote the first edition and carried the book through four revisions, the latest in 1924, prior to his death. The fifth edition in 1947, and the present volume, required the cooperation of a staff of writers especially qualified in the subjects treated. The new volume has twenty-two chapters with one-hundred fifty pages more than the fifth edition.

One can find little to criticize, and due recognition should be given the editor, Herbert R. Mauersberger, for the work involved obviously has been great. One is inclined to wonder if the next edition should be divided into two volumes. The present book is quite unwieldy.

The new features and up-to-date information make the new volume a must for every reference shelf.

History of American Industrial Science. Courtney Robert Hall. New York, Library Publishers, 1954. xix + 453 pages. Price, $4.95.

History of American Industrial Science deals broadly with the basic and technological phases of the larger divisions of American industry including many of their ramifications.

Professor Hall, whose main interest for many years has been the history of science and technology in the United States, has presented a comprehensive outline of the development under the free-enterprise system of the revolution in American industry. He has drawn upon up-to-date as well as historical information obtained from sixty of the leading corporations of America and has presented his material factually and without apparent bias. The book is interestingly written and is easy reading, and the reader will find many little-known or not well-remembered facts concerning the development of the companies and their products and their importance to our industrial picture.

In the words of the author: "Whether many of us fully appreciate the significance of American Industrial Science or not, it is certainly important that we begin to do so, for it has done more to make the United States a strong nation than any other activity we can name."

A Compilation of Abstracts Dealing with Effects of Nuclear Radiation on Polymers and Fiber-Forming Materials. Raleigh, North Carolina State College, School of Textiles, 1954. 19 pages. Price, $5.00.

Of the possible fields for the peacetime application of nuclear energy, one of the latest to be explored has to do with the modification of the properties of fibers and polymers. North Carolina State College has the first private nuclear reactor outside the control of the Atomic Energy Commission.

This survey has been compiled of those abstracts pertaining to radiation effects on polymers and fiber-forming materials, published in AEC's *Nuclear Science Abstracts,* as the basis of current and future research studies of radiation effects on fibers and polymers by the Department of Textile Research, School of Textiles, North Carolina State College.

It is pointed out that radiation usually deteriorates or improves polymers, but as yet insufficient work has been conducted to produce "rules" by which the effect can be predicted; also, that early work indicates the need for further studies of radiation of various intensities, at various temperatures, and using various media; and that such studies could lead to a better understanding of fiber structure and its relation to fiber properties.

The Structure of Textile Fibres—An Introductory Study. A. R. Urquhart and F. O. Howitt, Editors. Manchester, England, The Textile Institute, 1954. 165 pages. Price, 12/6 ($1.75).

The Structure of Textile Fibres comprises a series of articles which appeared in the Proceedings Section of the *Journal of the Textile Institute*. The articles were written in an attempt to describe the structure and properties of fibers as nearly as possible in a manner and with terminology that the layman can understand. In the sense that this is an introductory study the objective appears to have been reasonably well met, although an elementary knowledge of chemistry and physics is definitely helpful.

The organization of the book is excellent. The first three chapters—Why Are Fibres Fibrous, Fibres and Plastics, and Fibre Properties and Molecular Arrangement—furnish a background of elementary information necessary to an understanding of the chapters which follow. These in turn treat of the natural fibers, cotton, silk, wool, flax, and bast and leaf fibers in the order named, and then rayons, acetate, dispersed proteins, alginate, and the true synthetics. The modification of fiber properties by means of chemical treatments is discussed.

The Structure of Textile Fibers is definitely a book for the student, the textile nonscientist, and those persons in other fields who wish to enlarge their knowledge of textile materials.

Review of Textile Progress, Vol. IV. Published jointly by the Textile Institute, Manchester, England, and the Society of Dyers and Colourists, Leeds, England, 1954. 560 pages. Price, 35/ ($5.00).

Volume IV of the *Review of Textile Progress* presents a detailed discussion of progress in science and technology based principally on the technical literature and patents published during 1952. The same general pattern of the previous volumes has been followed. There are eleven principal sections similar to the divisions of the Abstracts Section of the *Journal of the Textile Institute*. Two subsections have been added, which deal with carpet manufacture and the production of regenerated protein fibers. Each subject has been contributed by a well-known British authority in the field. This book will be found to be valuable as source material and as reference for the researcher.

Manual of Cotton Spinning. Vol. I: **Raw Cotton Production and Marketing.** A. F. W. Coulson, Editor. Manchester, England, The Textile Institute, 1954. xiii + 222 pages. Price, 12/6 ($1.75).

The Textile Institute is planning to publish over the next few years a series of textbooks under the general title *Manual of Cotton Spinning,* which will cover the entire field of cotton spinning. This first volume is in the nature of an introductory survey and furnishes background knowledge essential to the student as well as to the cotton spinner and to every well-informed cotton man.

The book is divided into three sections. Section I deals with the history and economic background of the industry. Section II deals with the production of the raw material of the cotton industry. Section III explains the organization and operation of the world's cotton markets. The contributors are authorities in their respective fields.

Although, as might be expected, considerable attention is paid to the practices and experience of British industry, this does not belittle the importance to persons and organizations wherever they are located. This volume and those to follow will be useful additions to every bookshelf.

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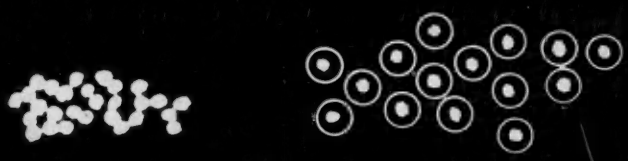

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